ADDIS ABABA SCIENCE AND TECHNOLOGY UNIVERSITY

COLLEGE OF ARCHITECTURE AND CIVIL ENGINEERING

SLOPE STABILITY ANALYSIS OF RAINFALL INDUCED LANDSLIDES

A CASE STUDY ON GOHATSION - DEJEN ROAD ABAY GORGE

Samuel Addisalem

A Thesis Submitted to

The School of Graduate Studies

Department of Civil Engineering

In Partial Fulfillment of the Requirement for Degree of Masters of Science in Civil Engineering

Advisor: Dr. Brook Abate

June, 2017

ADDIS ABABA SCIENCE AND TECHNOLOGY UNIVERSITY

SCHOOL OF GRADUATE STUDIES

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BY

SAMUEL ADDISALEM LEGESSE

COLLEGE OF ARCHITECTURE AND CIVIL ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

In Partial Fulfillment of the Requirement for

Degree of Masters of Science in

Civil Engineering (Geotechnical Engineering)

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I, Samuel Addisalem Legesse, declare that this thesis is my original work and it has not been presented and will not be presented by me to any other university for similar or any other degree award

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Date: ____________________________________

ABSTRACT

Slope failures triggered by rainfall are causing considerable damage and loss of life every year throughout the world. During rainy seasons landslide in Abay gorge has been causing: loss of human lives, failure of engineering structures, and damage on agricultural lands. This is due to the fact that, at dry seasons the ground can develop considerable amount of suction and this improves the shear strength of the soil in the area. In rainy season, when rainfall infiltrates into ground, suction decreases, while the shear strength also reduces, which may lead to slope instability.

In this study, a landslide at 10Km from the town of Gohatsion has been selected as a case study considering risk for road and hazard score values and the availability of the required data for the stability analysis. The required data for stability analysis were collected from fieldwork measurements and observations and from secondary sources mainly GSE and ERA.

A detail slope stability analysis was carried out based on limit equilibrium approach using SLOPE/W. Seepage analysis for the stability analysis were conducted by adopting finite element based software, called SEEP/W. The relationship of rainfall and slope stability was demonstrated by conducting the analysis for different rainfall durations and intensities.

The coupled hydro-geological stability analysis result reveals that, loss of suction due to rainfall infiltration is critical for the stability of landslide at 10km sta. The factor of safety during the rainy season shows significant reduction from its initial dry state value of 1.506 to 1.29 after 3-day rainfall duration. Finally, based on the stability analysis findings concluding remarks on the application of the study in landslide prediction and recommendations for further studies were clearly stated.

Key Words: Landslide, Seepage analysis, Stability analysis, Rainfall, Suction, Factor of Safety, SLOPE/W, SEEP/W.

Dedicated

To

My Beloved Father, AddisalemLegesse,

"Gashye I really Miss you"

ACKNOWLEDGMENTS

I would like to express my great gratitude and sincere thanks to my advisor, Dr. Brook Abate, for his continued inspiration, support and invaluable guidance during my study. Without his endless efforts and experienced guidance, it would not have been possible to complete this work.

With greatest appreciation I wish to express my acknowledgment to ERA for the scholarship funding and Addis Ababa Science and Technology University for full academic support.

Thanks to the Geological Survey of Ethiopia (GSE), Ethiopian Road Authority (ERA), and National Metrological Agency of Ethiopia, who kindly allowed me access to all available information on the Abay Gorge, and permitted the presentation of this slope as a case study.

Special gratitude is owed to Mr. Kassahun Luelseged, Mr. Abiy Tsegaye and the rest staff member of Ethiopian construction design and Supervision Corporation, water and energy design and supervision sector for their kind support throughout the study time.

To my family, specially my parents Addisalem Legesse and Yigardu Desse, and my sister Ager Addisalem, I would like to give the biggest gratitude that your supports and beliefs have strengthened me to achieve my dreams.

Ultimately, thanks to GOD, for all His mercy and compassion.

ACRONYMs

UTM – Universal Transvers Mercator

JICA – Japan International Cooperation Agency

GSE – Geological Survey of Ethiopia

WWIS-World Weather Information Service

SNNP – Southern nations, Nationalities and Peoples

AP – Associated Press

UN – United Nations

GEO – Geotechnical Engineering Office

FoS – Factor of Safety

LE - Limit Equilibrium

LEM-Limit Equilibrium Method

FE- Finite Element

FEM- Finite Element Method

ERA - Ethiopian Road Authority

EMA - Ethiopian Mapping Agency

BH-Bore Hole

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1. INTRODUCTION

1.1 General

Natural hazards such as earthquakes, landslides, avalanches, floods, cyclones, droughts, and volcanic eruptions of varying magnitudes has frequently been the cause of calamities. According to statistics, natural hazards are believed to account for up to 4 % of the total annual deaths worldwide, besides causing enormous economic losses and uprooting habitation, Dai and Lee, (2002).

Landslides are natural disasters and they cannot be stopped at times, especially when a landslide comes due to erosion. This is going to cause a lot of trouble and to be honest; it is very difficult to prevent this from happening because even though they can be human activity that contributes to this, not all are. A lot of the landslides are all natural disasters that come from problems with Mother Nature including problems with the soil and trouble with weather, Bates & Jackson (1987).

The weather can contribute to landslides and can be a terrible and ferocious disaster which cannot be tamed. This can result from a huge loss of life, severe damage to property as well as injure animals and damage landscape. It can be difficult also to understand how landslides work because many believe they can be stopped; the truth is that they can't and even though some are created by human activity, most are not. They are natural disasters and they can cause a lot of severe damage.

There have been many landslides throughout the years including the Rio de Janeiro landslide in 2011 which caused over 600 deaths. There are other major landslides including the Cairo landslide in 2008, the Devil's Slide in California and the Vargas mudslide which all caused a lot of damage and devastation. There has been dozens, hundreds in fact, across the world and it has been so difficult to know how to deal with a landslide. (Dai and Lee, 2002)

It is not just on earth in which landslides occur. Throughout the solar system there has been evidence that landslides have occurred. This includes on Mars and Venus in which have seen landslides. In fact, scientists have had trained satellites orbiting the planets to view the landslides.

1.2 Statement of the problem

The hilly and mountainous terrains of the highlands of Ethiopia which are characterized by variable topographical, geological, hydrological (surface and groundwater) and land-use conditions, are frequently affected by landslide slope failures triggered by different factors. Rainfall, soil structure change, earthquake and groundwater are natural triggering landslides factors. But human activities can also contribute to cause a landslide such as Heavy machine vibrations in the ground and Deforestation can make fragile slopes unstable.

Rainfall triggered landslides are common problems in many areas of the hilly and mountainous regions of the highlands of Ethiopia. Gezahegn (1998), Ayalew (1999),Temesgen et al. (2001), Nyssen et al. (2002), Ayalew & Yamagishi (2004), Ayenew & Barbieri (2004), Woldearegay et al. (2004) indicate landslides in these terrains have been affecting human lives, infrastructures, agricultural lands and the natural environment.

Although landslides have been observed for at least the last three decades, in more recent times the sensitivity of both the public and administrative bodies to these events has increased as more and more people are now living in the affected areas.

Indeed, landslides or landslide generated problems have claimed about 300 lives, damaged over 100 km of asphalt road, demolished more than 200 dwelling houses and devastated in excess of 500 ha of land in Ethiopia in the years 1991-1998 (Ayalew, 1999). Even in the year 2016at least 50 people have been killed in flooding and landslide caused by heavy rains in Ethiopia some 41 people died in Wolayita Zone in southern Ethiopia because of the landslide and tens of thousands of people have been affected by heavy rains in several parts of the country. A number of roads have been washed away and bridges destroyed.

Despite this, however, the causes and mechanisms of slope failures remain poorly understood and so far, insufficient effort has been made to reduce losses from landslides and landslide-generated hazards. In order to minimize such damages delineation of landslide prone areas has a vital role. By referring landslide susceptibility zonation maps, susceptible areas can be identified and the necessary action can be taken to reduce or avoid the associated hazard and risk that could have been occurred otherwise. Until recently, this was not common in developing countries. This leads to additional maintenance cost, most of the time very expensive and in some cases impossible. Almost all of landslides in Ethiopia occur during the rainy season (June to September) and at these times a large scale landslide occurs especially in the Abay gorge which incorporates the national highway No. 3.During the landslide times the road pavement damaged and sometimes it will be closed for traffic.

As it is mentioned above the problem is frequent during the rainy season; which indicates that the landslide is mainly triggered by rainfall. Hence, lack of appropriate slope stability analysis of rainfall induced landslide types is believed to have played an adverse role in aggravating the landslide problem in the area.

1.3 Objectives of the Study

1.3.1 General Objectives

The general objective of the study is to investigate the effect of rainfall in causing landslide slope failures on the Abay Gorge Gohatsion – Dejen Road which is the trunk road, using geotechnical computer applications based on geological, topographic, hydrological and geotechnical data along with the available landslide monitoring data borehole and laboratory data.

1.3.2 Specific Objectives

Objectives of the research works are:

- ➔ To determine and understand the effect of rainfall in causing landslide slope failures on the case study area.
- ➔ To analyze the stability of existing slopes along Gohatsion - Dejen road using coupled hydrological-slope stability using modeling computer applications SEEP/W and SLOPE/W (Geo-Studio 2007).
- ➔ To investigate how the loss of suction or Negative Pore Pressure in unsaturated soil affects slope stability.
- ➔ To find out factors of safety of potential landslide locations in the Abay Gorge during rainfall.
- ➔ To enable the planning and design of preventive and remedial measures more effective, economical and sound, where ever necessary.

1.4 Significance of the Study

The significance of the study is to investigate the effect and extent of rainfall in causing landslide slope failures in the Abay Gorge Gohatsion- Dejen Road and to determine factor of safety before and after rainfall as infiltration decrease the matric suction and increases the ground water level of the study area.

Moreover, if material and data availability constraints conquered the study will strive to illustrate defined relationship between rainfall and landslide. Besides, the study will undertake stability analysis of landslides induced by rainfall and in combination with other triggering factors for landslide slope failure.

In addition, the research work may be used as an input for other researchers who have passion in detail investigation and analysis of rainfall induced landslides in other parts of Ethiopia in particular and the world in general.

2. LITERATURE REVIEW

2.1 General

Landslides constitute a major threat to both lives and property worldwide, especially in tropical and subtropical areas such as South America, Africa and the Far East. These regions are characterized by periods of prolonged dry weather with periods of intense rainfall. In the stability analysis of landslide, rainfall is a very important factor.

A large amount of statistical data shows that most of landslides occur after a rainfall or during a rainfall. There exists a law that landslides increase with increased rainfall in a region. Such rain-induced landslide and slope failure are the most common ones in many countries such as Japan, Hong Kong, and Southeast Asia. With the development of percolation theory of saturated and unsaturated soil, all over the world, researchers have been increasingly aware that the occurrences of soil slopes have close relationship with soil unsaturated seepage in rainy season. The physical process of rainfall infiltration into ground and its seepage through unsaturated-saturated soils has been studied by hydro-geologists, soil scientists, and geotechnical researchers.

2.2 History of Landslide in Ethiopia

In order to become a middle income country in the next two decades, Ethiopia is currently involved in massive infrastructural development (including roads, railways dams), urban development and extensive natural resources management. However, in rainy seasons these infrastructure development works face a huge risk of failure and damage from landslide and other slope failure. Especially, the hilly and mountainous terrains of the highlands of Ethiopia are frequently affected by rainfall-induced landslides of different types and sizes. The major types of landslides reported to have been triggered by heavy rainfalls include debris/earth slides, debris/earth flows and, medium to large-scale rockslides.

Except for the efforts made by the Ethiopian Geological Survey (GSE), Ethiopian Roads Authority (ERA) and Japan International Cooperation Agency (JICA) so far there is no comprehensive inventory of landslides and their significance (economic, social and environmental) is made in Ethiopia. However, despite multi-face challenges in landslide research in the country, several authors have reported on slope instability problems in different parts of country. A summary of the major landslides reported so far in the country are summarized below.

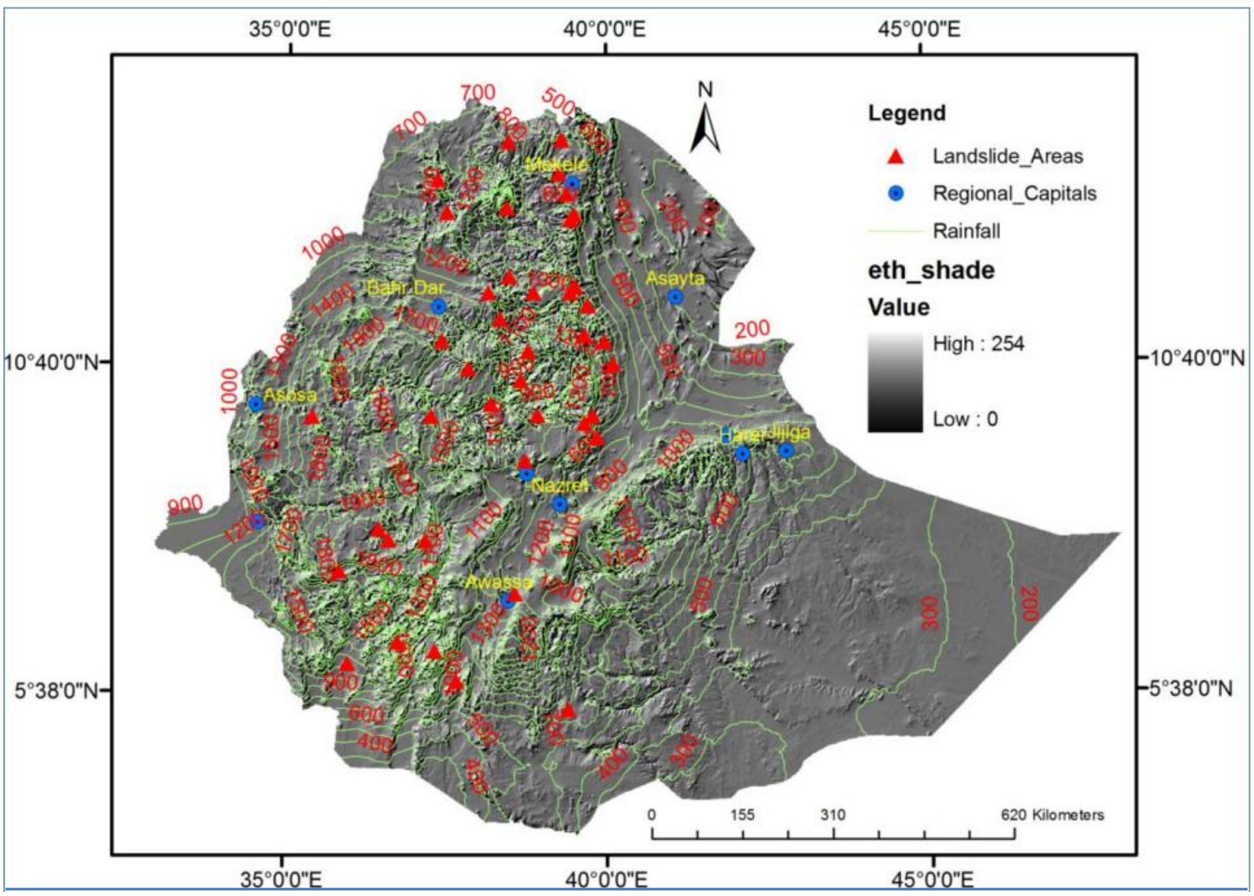

Fig. 2.1 Locations of landslide affected areas in the highlands of Ethiopia. Ayalew (1999), Woldearegay et al. (2005)

2.2.1 Landslide in Dessie Town

The town of Dessie, a medium-sized urban settlement with about 200,000 inhabitants, and the surrounding area are heavily affected by landslides (GSE, 1995; Ayalew and Vernier, 1999; Ayenew and Barbieri, 2005; Fubelli et al., 2008). The town is located in one of the small tectonic depressions of the western Afar Margin, a physiographic province characterized by closed basins and mountain ranges produced by Tertiary–Quaternary regional extension (Ukstins et al., 2002).

The main triggering factor of most landslides in the area is heavy rainfall (Ayenew and Barbieri, 2005). Rapid slope failures such as rock falls and debris flows, are also triggered by earthquakes (Gouin, 1979), as it occurred during the seismic event of 8 July 1988.

2.2.2 Landslide in Wondo Genet

Wendo Genet is located on the inner slope of a caldera in the eastern margin of the Main Ethiopian Rift. The bedrock is made up of basalts and ignimbrites. Mass movements are frequent in Wendo Genet (Temesgen et al., 2001) in spite of the thick vegetation cover on the surrounding slopes. Mud flows and soil slips in eluvial–colluvial deposits, with basal shear surfaces at the bedrock contact are triggered by long-lasting heavy rainfall and water infiltration into the soil.

The occurrence of these failures is also favored by the intensive cultivation of the slopes with irrigation ditches parallel to the contour lines. Eight people lost their lives due to a debris flow triggered by the heavy rains of June 17, 1996 (Temesgen et al., 1999).

2.2.3 Landslide in Abay (Blue Nile) Gorge

The slopes of the Blue Nile Gorge are widely affected by different types of mass movements (GSE, 1994; Ayalew and Yamagishi, 2002, 2004) which have repeatedly damaged and interrupted the Addis Ababa – Bahir Dar road. In 1960, after a long preparatory phase, characterized by the development of small soil slips, a large-scale rotational slide suddenly moved downslope destroying a village and causing 45 victims (Ayalew, 1999).

2.2.4 Landslides in Jemma basin,

The Jemma basin which is a tributary of the Blue Nile River is reported to have been affected by landslides of different types and sizes. As part of the development cooperation program among GSE, Aquatest, and Czech Republic Development Cooperation, a comprehensive study on the Water Resources Management and Environmental Protection Studies was made for the Jemma basin. Part of this project output, Sima et al. (2009), and Zvelebi et al (2010) have reported on the prevalence of geo-hazards (like landslides) in the Jemma basin.

2.2.5. Landslides in Goffa,

Landslides were reported in southern highlands of Ethiopia: Asrat et al (1996) and Lemessa et al. (2000) have studied slope failures in the Goffa area. According to these authors the slope instability in these areas mainly involved earth/debris materials.

2.2.6. Most Recent Landslides

The Ethiopian Roads Authority has seen a significant increase in landslides as the road network has continued to expand over the last 20 years. The usual impact of these landslides on Ethiopian roads is long-term and progressive slope movement, often triggered by heavy rainfall. Shear surfaces are often shallow, occurring for example in black cotton soils and weathered tuffs. The majority of slope failures affecting the network involves cut slopes or fills slopes where weak horizons are exposed or overlain.

Landslide in SNNP

In the year 2015 at least 41 people were killed due to landslides triggered by heavy rains in Wolaita zone, SNNP regional state of Ethiopia, in five districts according to a report by local media, Fana Broadcasting Corporate (FBC). Moreover, a road linking Wolaita zone with Dawro zone and a bridge which connects Wolaita town with Sidama zone have been damaged by the landslide and floods, said the report.

According to AP Ethiopia is struggling with the worst drought in 50 years, but unseasonably heavy rain is also causing massive damage in many parts of the country. About 100 people have been killed by floods and landslides across Ethiopia in 2016 that started last month June, government officials say.

At least 20,000 families have been made homeless in 2016, according to the UN. Meteorologists have blamed this year's particularly powerful El Nino weather phenomenon for the country's high rainfall.

2.3 Types and Causes of Landslide Slope Failure

Landslides show differences in the type of material and motion involved in the process. Therefore, classification of landslides usually takes in to account the type of material involved and the type of movement mechanism (Dai and Lee, 2002). Although one type of movement generally dominates over the others in certain areas of the moving mass or at certain times of the movement, actual landslides are usually complex in that they include different types of materials and a combination of different movements (Vinh, 2007). It is important to have a well-organized classification scheme in order to understand these slope movements.

They can be classified in many ways according to particular purpose (Long, 2008). The most widely used classification is the one developed by Varnes (1978). This takes in to account both the type of material and the type of movement in combination for the classification of landslides in to different types. This classification scheme is presented in Table 3.1.

TABLE 2. 1CLASSIFICATION OF SLOPE MOVEMENTS FROM VARNES (1978)

Type of movement	**Type of material**		
	Bed Rock	**Soil**	
		Coarse	**Fine**
Falls	Rock Fall	Debris Fall	Earth Fall
Topples	Rock Topple	Debris Topple	Earth Topple
Rotational Slide	Rock Slump	Debris Slump	Earth Slump
Translational Slides	Rock Block Slide	Debris Block Slide	Earth Block Slide
	Rock Slide	Debris Slide	Earth Slide
Lateral Spreads	Rock Spread	Debris Spread	Earth Spread
Flows	Rock Flow (Deep Creep)	Debris Flow (Deep Creep)	Earth Flow (Deep Creep)

Some of the landslides presented in Table-3.1 are described below.

2.3.1 Falls

Fall is a sudden vertical movement of material from a cliff by the pull of gravity, the falling material can be a single rock dislodged from a steep slope or a sudden collapse of mass of rock falls down a slope by freely falling, rolling, bouncing and sliding until friction and decreasing slope angle at the base of the cliff halts its motion (Murck et al., 1996). Depending on the material involved in the fall it can be divided as follows

- Rock fall: when the falling material is a block of rock or rocks fragmented in to pieces due to collision with other rocks on the lower part of the slope. Rock falls are common occurrences at the base of cliffs and steep slopes. As mentioned by Log (2008) the typical slope angles involved is between 450 and 900.

- Debris fall: when the overlying sediment and plants are dislodged with the rock producing a mixture of rock, weathered regolith and vegetation.
- Earth fall: when the falling material consists more than 80% fine particles of less than 2 mm (Varnes, 1978).

2.3.2 Topple

Varnes (1978) defined topple as a mass movement that consists of the forward rotation of mass of rock or soil about some pivot point, below the displaced mass. The forces responsible for the rotation are the action of gravity, forces exerted by adjacent units or freezing and thawing of fluid in cracks.

2.3.3 Slide

Slide is a down slope movement of earth material on a well-defined inclined surface. The movement is translational and there is little internal shear, the movement is restricted to the failure surface. Therefore, trees and structures on the surface may stay relatively intact. Barbaraet al. (1996) mentioned faults, foliation planes in metamorphic rocks or layering in sedimentary rocks or alternating sequences of rock types as some of the possible failure surfaces where slide can occur.

2.3.4 Slump

Slump is a type of slope failure which involves a downward and out ward movement of rock or regolith on a concave up failure surface. Slumps can range from small displacements of one or two square meters to large complexes of hundreds or thousands of square meters (Murck et al., 1996). Slumps usually result from artificial modifications of slopes (Murck et al., 1996). Therefore, they are common around highways where bordering slopes have been over steepened by construction.

2.4 Factors influencing slope stability

The equilibrium status of a natural slope can be affected by several direct or indirect factors. In every slope there are forces which tend to promote down slope movement and opposing forces which tend to resist movement. A change in any one or a combination of these factors can alter the equilibrium condition of slope, decreasing its stability and sometimes leading to the slope failure.

This change may be caused by natural processes such as the faulting, rivers undercutting the toe of a slope or bank scouring by debris flows etc. and also anthropogenic activities such as excavation, cultivation or removal of material may also cause change in slopes. Varnes (1978) pointed out that there are a number of external or internal causes which may be operating either to reduce the shearing resistance or to increase the shearing stresses. Slope instability factors can be causative factor or triggering factor. Causes may be considered to be factors that make the slope vulnerable to failure, that predispose the slope becoming unstable while the trigger is the single event that finally initiates the landslide. Some of the major factors which influence the slope stability are described below.

2.4.1 Geological factors

Landslide events are strongly controlled by the nature of the regolith material (Thomson, 1971; Sawnston, 1978; Yokota & Iwamatsu, 1999; Wakatsuki et al., 2005). Failure commonly occurs along bedrock bedding planes that are deep-seated and dip in the same direction as the slope surface. In saturated conditions, incompetent material may fail under overburden weight and high pore pressures, resulting in a deep-seated rotational-type failure. Translational slides commonly are controlled structurally by surfaces of weakness such as faults, joints, bedding planes, and contacts between bedrock and overlying deposits (Sidle & Ochiai, 2006). Generally slope stability is influenced by the following geological factors: Engineering-geological properties, Geological structures and Stresses in geological history

2.4.2 Soil Properties

Both the hydraulic properties and the shear strength behaviors of soils can affect the stability of a slope with or without a rainstorm. Another attributed effect is the presence of soils that contain a high proportion of a type of clay mineral called smectites or montmorillinites. Such clay minerals expand when they become wet as water enters the crystal structure and increases the volume of the mineral. When such clays dry out, the loss of water causes the volume to decrease and the clays to shrink or compact. Failure is attributed with pore water pressure built up on such soils.

2.4.3 Topographic and Geomorphologic factors

2.4.3.1 Slope Gradient

Slope angle controls the gravitational driving most geomorphic work and thus debris flow initiation and debris transport (Jakob, 1996). In general the steeper the slope, the more the risk of landslide due to the higher shear induced by gravity, although various types of landslide are related to certain slope range. For example, the initiation of debris flow is related to the slope of the source areas, with typical values between 27^{o} and 38^{o} (Takahashi, 1981; Hungr et al., 1984; Rickmann and Zimmermann, 1993). Watershed slope is important feature and is usually used to represent the geomorphologic and landslide characteristics of discriminate analysis on debris flow streams. Although different studies indicated different ranges of slope in each steps of the debris processes, generally speaking slope angle of initiation of debris flow > slope angle of transportation > than angle of deposition.

2.4.3.2 Aspect

The aspect of a slope is defined as the horizontal direction to which a slope faces. In other words, it shows the direction of maximum slope of a surface. It can influence landslide initiation. The amount and distribution of precipitation received on a particular slope differs with respect to the various orientations it could have. Aspect related parameters such as exposure to sunlight, drying winds, rainfall (degree of saturation), and discontinuities may control the occurrence of landslides (Dai & Lee, 2002). This means that slopes similar in inclination, materials and geology may behave differently depending on their aspect which may control moisture, seepage and pore-water pressures and so on. However, the direct correlation between aspect and landslides is not yet clear (Van Westen, et al, 2006)

2.4.3.3 Elevation

The influence of elevation on the mechanism of land sliding is often attributed to be indirect. In general, precipitation, weathering processes, erosion and resulting weathering depths, soil thickness, land use are influenced by elevation. The strong statistical relationship between elevation and landslide occurrence has been mentioned in several studies (e.g. Gritzner, et al, 2001; Dai and Lee, 2002). The more intense erosion and weathering, the more will be the influence of elevation on landslides. Thus, considering elevation as one of the causative factors is reasonable from the perspective of other elevation affected processes that control landslides.

2.4.3.4 Drainage factors

In addition to rainfall, erosive action of streams also contributes to slope instabilities. Streams erode sides of their valley which leads to instability of the slope area surrounding it (Bathrellos, et al, 2009). This is due to undercutting action of streams. The closer the slope is to streams, the more likely will it get water and develop pore pressure. Streams may adversely affect stability by eroding slopes or by saturating the lower part of the material which results in an increase in ground water level. Therefore, distance to stream is one of the information to be collected in most landslide susceptibility zonation and early warning system preparation.

2.4.3.5 Land use factor

Land use and land use changes caused by human and natural factors, are one of the causative factors which may influence the mass movements and sediment supply susceptibility of a catchment. Improper slope land cultivation, removal of vegetative cover, and road construction can contribute to the occurrence of landslides and debris flows in a catchment.

A description of the types and density of vegetation and land use provides information on the possible effects of land use on surface-water runoff and erosion (Richard, 2005). Land development may remove vegetation and expose soils, promoting erosion, increasing sediment yield and decreasing natural slope stability within the drainage basin and often creates impervious surfaces that increase the rate and volume of runoff (Richard, 2005). Also, Garfi, et al, (2006) recognizes vegetation cover as a significant control on the sediment generation processes acting within fan catchments. Once this vegetation is removed slopes increasingly become prone to erosion through mass movements or water flows. Conversely, the presence of vegetation can alter the severity of debris flows by contributing additional vegetative debris to the flow (Selby, 1974)

2.4.4 Hydrological factors

Hydrology plays a crucial role in landslide initiation. Some of the major significant hydrologic processes include spatial and temporal distribution of rainfall, water recharge and discharge areas, lateral and vertical movement within the regolith, and the likes.

2.4.4.1 Precipitation

The most common trigger of landslide is sufficient water input during precipitation events. Rainfall is considered the most frequent landslide-triggering factor in many regions of the world (Corominas, 2001).The frequency and magnitude of rainfall events, together with other factors such as lithology, morphology and land cover, influences the type of landslide (Van Ash et al., 1999; Crosta, 1998). Generally, deep-seated landslides are often triggered by moderate intensity rainfall distributed over long periods whereas superficial landslides such as soil slips and debris flows are triggered by short duration, intense precipitation (Corominas, 2001). During intense rainfall events the variations in pore water pressures distributed within the soil are highly variable depending on the hydraulic conductivity, topography, degree of weathering, and fracturing of the soil. Pore-water pressure increases may be directly related to rainfall infiltration and percolation or may be the result of the build-up of a perched or groundwater table (Terlien, 1998). The response of the material involved is largely dependent on its permeability. In high-permeability soils the build-up and dissipation of positive pore pressures during intense precipitation events could be very rapid (Johnson and Sitar, 1990). In these cases slope failures are caused by high intensity rainfall and antecedent rainfall has little influence on landslide occurrence (Corominas, 2001). On the contrary, in low-permeability soils slope failures are caused by long duration-moderate intensity rainfall events; in fact, the reduction in soil suction and the increase in pore water pressures due to antecedent rainfall is considered a necessary condition for landslide occurrence (Sanderson et al., 1996; Wieczorek, 1987).

2.4.4.2 Groundwater

Groundwater is another factor that plays role in landslide initiation. Geology in turn influences the flow of groundwater, its direction, pressure and gradient at any point within a slope. Chowdhury (2010) states that water can influence the strength of the materials by: (1) chemical alteration and solution, (2) reduction of apparent cohesion due to capillary forces, which disappear on submergence or saturation, (3) increasing pore water pressures with consequent reduction of shear strength. The same author also mentioned that increase of pore water pressures due to the flow of groundwater is an important factor in the development of slope failures and the occurrence of landslides. In particular the presence of groundwater under pressure often facilitates severe slides of the flow type.

Thus, groundwater flow increases the slope failure potential and its effect is highest for seepage areas. These researchers also showed a large influence of the saturated permeability distribution within slopes on slope stability.

2.4.5 Seismicity factors

Earthquake is one of the principal triggering factors of landslides that cause great hazard to both of life and properties loss. The vibration released during earthquakes can cause failure of slopes which were previously stable. The possibility of an earthquake in triggering a landslide event depends on the shaking of the ground rather than on the actual magnitude of the earthquake (Muthu and Petrou, 2007). The vibrations released during a quake can cause resettlement of the soil skeleton which in turn causes expulsion of water.

Earthquakes reduce stability by imparting both a shearing stress and a reduction in resistance to slope material. Earthquake wave propagation has three principal effects (Crozier, 1986; Alexander, 1993) which includes (1) the direct mechanical effect of horizontal acceleration, which provides a temporary increment to shearing stress (2) the cyclic loading which weakens inter-particle bonding causing liquefaction and (3) the reduction in inter-granular bonding by sudden shock irrespective of the degree of saturation.

According to Cornforth (2005) earthquake induced landslides can be grouped into: a) failure of marginally stable slopes which include ancient landslide terrain, actively eroding river banks, man-made cuts and fills on steep terrain, talus slopes, weathered rock faces, and stratified volcano slopes b) translational slide movements in clay soils-which commonly occurred in clay slopes were under normal static conditions, but become unstable when subjected to horizontal earthquake shock c) liquefaction of cohesion less soils common in course grained soils.

2.5 Fluid Flow Analysis

The analyses and simulations of slope failures are complicated. Many different assumptions are made in these analyses and many numerical models have been developed. Various models on different components of slope stability analyses are presented, including the relationship between rainfall and landslides, the water infiltration processes, and the relationship of the coefficient of permeability in unsaturated soil with the degree of saturation.

2.5.1 Relationship between Rainfall and Landslides

In the Abay gorge, during rainy seasons i.e. from June to September the landslide times the road pavement damaged and sometimes it will be closed for traffic. Tadesseet al. (1994) mentioned that, the 1959's landslide catastrophe in the Abay Gorge has claimed over thousands of live and property in a village called Gembecha in the area. According to them, landslide related failure of bridge and road are historically recorded in the area. Gezahegn and Dessie (1994) indicated the severity of the landslide problem on the main road in the area. The intensive rainfall may cause rapid rise of groundwater table and reduce the factor of safety of a slope against sliding.

From 1984 to 1990, 1790 landslides occurred due to the heavy rainstorms (GEO reports, 1984-1990). In 1997 and 1998, 72% of the landslides in Hong Kong are due to the adverse effects induced by groundwater (Wong and Ho, 1997). Since the rainfall-induced landslide is the major failure type in Hong Kong, studying the relationship between rainfall intensity and landslide occurrence can contribute to landslide prediction and prevention.

This relationship was first studied by Lumb (1975). He studied the recurrence of slope failures in residual soils in Hong Kong for the period 1950 to 1973. He suggested that the probability of landslides was related to the total amount of rainfall of the preceding 15 days. However, as the improvement of rain gauges allows shorter output time intervals, Brand et al. (1984) proposed different conclusions. They found that a large number of landslides were induced by short duration rainfall with high intensity, and the amount of preceding rainfall was not a significant indicator for the occurrences of landslides.

They also pointed out that the 24-hour rainfall was more related to the occurrences of landslides. Finlay et al. (1997) concluded that the probability of landslides should be predicted by the 3- 19 hour rainfall preceding the landslide. Dai et al. (2001) showed that the application of 12-h rolling rainfall would be more reliable.

It is apparent that the results of different studies draw different conclusions as to the significance of rainfall duration. This is because the results of these studies do not take into account the physical failure mechanisms and slope properties. They were just exercises of correlations between the slope failure and the amount of rainfall preceding the slope failure. Therefore, the relationship between rainfall and landslides is a case-specific problem and unique for different slopes.

2.5.2 Physical Processes of Infiltration

Slope instability in unsaturated soils occurs around the world and is attracting increasing attention in many studies (Ng & Shi, 1998). The unsaturated soils often occur at the shallow depth of the slopes. Pore-water pressure in unsaturated soils is usually negative relative to the atmospheric pressure as a result of soil matric suction. The infiltration of rainwater from the slope surface will increase pore-water pressure or reduce the soil matric suction, resulting in the decrease in shear strength of soils and loss of equilibrium. Therefore, the infiltration of rainwater into the sub-surface plays an important role in slope stability.

2.5.3Hydraulic Conductivity of Unsaturated Soils

In the process of water infiltration into unsaturated soil, as mentioned above, the soil hydraulic conductivity is dependent on the degree of saturation (Sw) and the matric suction (φ). Before rainfall events, matric suction occurs in the unsaturated soil above the groundwater table. During the rainfall, soil matric suction decreases as the degree of saturation increases. Due to the hysteretic effect of water filling into the pores of soil, the value of soil hydraulic conductivity is smaller than that in a saturated state and it will increase with the increase in degree of saturation.

The ratio of the effective hydraulic conductivity in the unsaturated zone to the saturated hydraulic conductivity is defined as relative hydraulic conductivity, denoted as K_r. Therefore, establishment of the constitutive relations among φ, S_w and k_r is necessary to solve infiltration problems. Two classic models and equations are summarized in the following sections.

2.5.3.1 Brooks-Corey Model

Brooks and Corey (1964) developed a model for water retention function and unsaturated hydraulic conductivity. The soil water retention function is given by:

$$\boldsymbol{S_e = |\varphi/h_a|^{-\lambda} \quad for\ \varphi < -h_a} \tag{2.1}$$

$$\boldsymbol{S_e = 1 \qquad\qquad for\ \varphi \geq -h_a} \tag{2.2}$$

And the relative hydraulic conductivity is obtained from:

$$k_r = S_e^{(2/\lambda + l_p + 2)} \quad (2.3)$$

Where h_a = air-entry pressure head (m); λ = pore-size distribution index (dimensionless); φ = pressure head (m); $\boldsymbol{l_p}$ = pore-connectivity parameter [assumed to be 2.0 in Brooks and Corey (1964)]; and S_e= effective saturation given by:

$$S_e = (S_w - S_{wr})/(1 - S_{wr}) \quad (2.4)$$

With $\boldsymbol{S_{wr}}$= residual water saturation (dimensionless).

2.5.3.2 Van Genuchten Model

According to the earlier work by Mualem (1976), Van Genuchten (1980) developed another model. For the soil water retention function, it is defined by:

$$S_e = (1 - |\alpha\varphi|^{\beta})^{-v} \quad for\ \varphi < 0 \quad (2.5)$$

$$S_e = 1 \quad for\ \varphi \geq 0 \quad (2.6)$$

And the relative hydraulic conductivity is described by:

$$k_r = S_e^{(l_p)}\left[1 - \left(1 - S_e^{1/v}\right)^{v}\right]^2 \quad (2.7)$$

Where

$$v = 1 - 1/\beta \qquad \beta > 1 \quad (2.8)$$

Where α and β = Van Genuchten parameters and they are obtained from a fit of the functions to experimental results. In this model, the value of poreconnectivity parameter l_p was estimated to be 0.5 by Mualem (1976).

Many studies were conducted on the estimation of Van Genuchten parameters by either direct measurements or mathematical functions.

A more comprehensive prediction was published by Schaap and Leij (1998). They listed the average and standard deviations of the Van Genuchten parameters and saturated hydraulic conductivities (K_s), for different soil texture classes as tabulated in Table 3.2.

In general, the Brooks-Corey Model and the Van Genuchten Model are the two most popular models to define the soil water retention function and unsaturated hydraulic conductivity. In the literature, it is well accepted that the Van Genuchten model matches experimental data more satisfactorily than the Brooks Corey model. However, the functions in Van Genuchten model is more complicated than Brooks-Corey model. In mathematical analysis, the Brooks Corey model is easier to be manipulated than the Van Genuchten model.

TABLE 2. 2MEAN VALUES AND STANDARD DEVIATIONS OF A AND B (SCHAAP AND LEIJ,1998)

Class	$\log(\alpha)$	$\log(\beta)$	$\log(K_s)$
	$\log(cm^{-1})$		$\log(cm \bullet d^{-1})$
Sand	-1.45 (0.25)	0.50 (0.18)	2.81 (0.59)
Loamy sand	-1.46 (0.47)	0.24 (0.16)	2.02 (0.64)
Loam	-1.95 (0.73)	0.17 (0.13)	1.08 (0.92)
Sandy loam	-1.57 (0.45)	0.16 (0.11)	1.58 (0.66)
Silt loam	-2.30 (0.57)	0.22 (0.14)	1.26 (0.74)
Sandy clay loam	-1.68 (0.71)	0.12 (0.12)	1.12 (0.85)
Silty clay loam	-2.08 (0.59)	0.18 (0.13)	1.05 (0.76)
Clay loam	-1.80 (0.69)	0.15 (0.12)	0.91 (1.09)
Silt	-2.18 (0.30)	0.22 (0.13)	1.64 (0.27)
Clay	-1.82 (0.68)	0.10 (0.07)	1.17 (0.92)
Sand clay	-1.48 (0.57)	0.08 (0.06)	1.06 (0.89)
Silty clay	-1.79 (0.64)	0.12 (0.10)	0.98 (0.57)

2.6 Slope Stability Analyses

In most cases, slope failures are usually caused by gravitational and seepage forces. Some researchers also argued that a primary factor leading to failure is the slope's own "mass". For example, a steep slope may be under higher risk off ailing rather than a mild slope. However, it is also common that many steep slopes are standing for years while some mild slopes fail during rainstorms. In past decades of studies, it has been well accepted that the pore-water pressure build-up in slope is the most crucial factors triggering slope failure (Sweeney and Robertson, 1979; Chipp et al., 1982; Pitts, 1983; Tan, 1987). The increase in pore-water pressure will decrease the shear strength of the soil, thus triggering instability on the failure plan. Conventionally, slope stability analysis is usually assessed by the limit equilibrium approach in a two-dimensional model. On the other hand, finite element approach is also getting more and more popular in recent studies. The principles of the two approaches will be discussed.

2.6.1 Types of Slopes

Gravity would tend to flatten out slopes, if it was not for the cohesion and friction forces of rocks and soils. However, the stability conditions may change due to temporary adjustments of equilibrium or because of external perturbations. Based on the position of the assumed slip surface as well as considering the height and length, slopes may be classified as finite and infinite.

2.6.1.1 Infinite Slope

Infinite slopes have dimensions that extended over great distances and the soil mass is inclined to the horizontal. If different strata are present strata boundariesare assumed to be parallel to the surface. Failure is assumed to occur along a plane parallel to the surface.

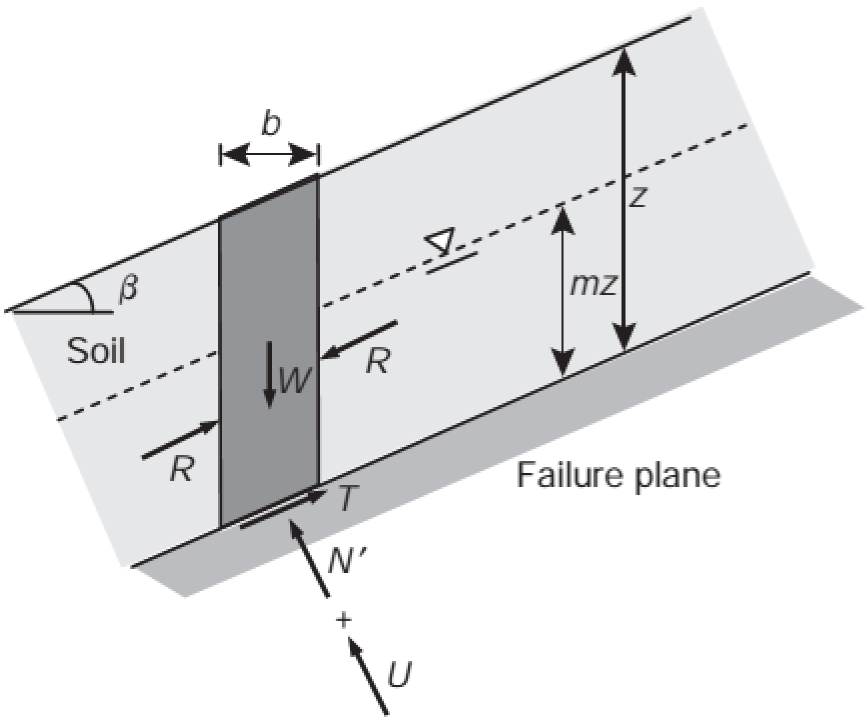

Fig. 3.3 Typical example of infinite slope

The factor of safety is as a ratio of shear strength of the soil to the shear stress and can be expressed as follows.

The shear strength along the failure plane is given by:

$$\tau = c' + (\sigma_n - u_w)\tan\phi'$$

$$= c' + [m\gamma' + (1-m)\gamma_m] z\cos^2\beta \tan\phi' \qquad (2.9)$$

The shear strength mobilized along the failure plane is given by:

$$\tau_{mob} = \frac{T}{b/\cos\beta} = \frac{w\cos\beta}{b/\cos\beta}$$

$$= [m\,\gamma_{sat} + (1-m)\gamma_m]\, z\sin\beta\cos\beta \qquad (2.10)$$

$$\therefore FS = \frac{c' + [m\gamma' + (1-m)\gamma_m] z cos^2\beta \, tan\phi'}{[m\,\gamma_{sat} + (1-m)\gamma_m]\, z \, sin\,\beta \, cos\,\beta} \tag{2.11}$$

2.6.1.2 Infinite Slope

A finite slope is one with a base and top surface, the height being limited. The inclined faces of earth dams, embankments, excavation and the like are all finite slopes. Investigation of the stability of finite slopes involves the following steps

a) assuming a possible slip surface,
b) studying the equilibrium of the forces acting on this surface, and
c) Repeating the process until the worst slip surface, that is, the one with minimum margin of safety is found.

Methods:-

I. Total stress analysis for purely cohesive soil
II. Total stress analysis for cohesive –frictional (c-φ) soil – (Swedish method of slices or Method of slices)
III. Effective stress analysis for conditions of steady seepage, rapid drawdown and immediately after construction.
IV. Friction circle method
V. Taylor's method.

2.6.2 Limit Equilibrium Methods

The limit equilibrium methods are adopted in many computer programs to assess slope stability. It is based on the Mohr-Coulomb criteria. The slope is primarily considered to fail along an assumed surface (slip surface). The slip surface can be circular, composite or of any shape. In saturated soils, for an effective stress analysis, the shear strength of soil is given by:

$$\tau = c' + (\sigma_n - u_w)\, tan\,\phi' \tag{2.13}$$

Where $\boldsymbol{\tau}$ = shear strength of soil (kPa); $\boldsymbol{c'}$ = effective cohesion of soil (kPa); $\boldsymbol{\sigma_n}$= total normal stress (kPa); $\mathbf{u_w}$= pore-water pressure (kPa) and $\boldsymbol{\phi'}$ = the effective angle of internal friction of soil (°).

For a total stress analysis, the parameters can be defined in terms of total stress and the pore-water pressure is not required in Equation (3.9). In unsaturated soils, the shear strength equation (3.9) is extended by combining the effective cohesion, net normal stress state and the matric suction linearly, which was modified by Fredlund et al. (1978) and gives:

$$\boldsymbol{\tau = c' + (\sigma_n - u_w)\tan\phi' + (u_a - n_w)\tan\phi^b} \qquad (2.14)$$

Where u_a = pore air pressure on the failure plan (kPa); and $\boldsymbol{\phi^b}$= angle defining the increase in shear strength for an increase in matrix suction (°). According to the study by Gan et al. (1996), the value of ϕ^b is not likely to be greater than $\boldsymbol{\phi'}$.

Normally, when a failure surface is assumed, the slope mass above the surface is divided into a number of vertical slices. The free body diagram of a slice is shown in Figure 3.4.

Based on this surface, the shear strength of soil τ is calculated and compared with the shear strength required to maintain a limiting equilibrium condition (τ_m'). In practice, a factor of safety (FOS) $F_s$is introduced and given by:

$$\boldsymbol{F_s = \tau/\tau_m} \qquad (2.15)$$

Therefore, the magnitude of the shear force T at each slice can be calculated as:

$$\boldsymbol{T = \tau l/F_s} \qquad (2.16)$$

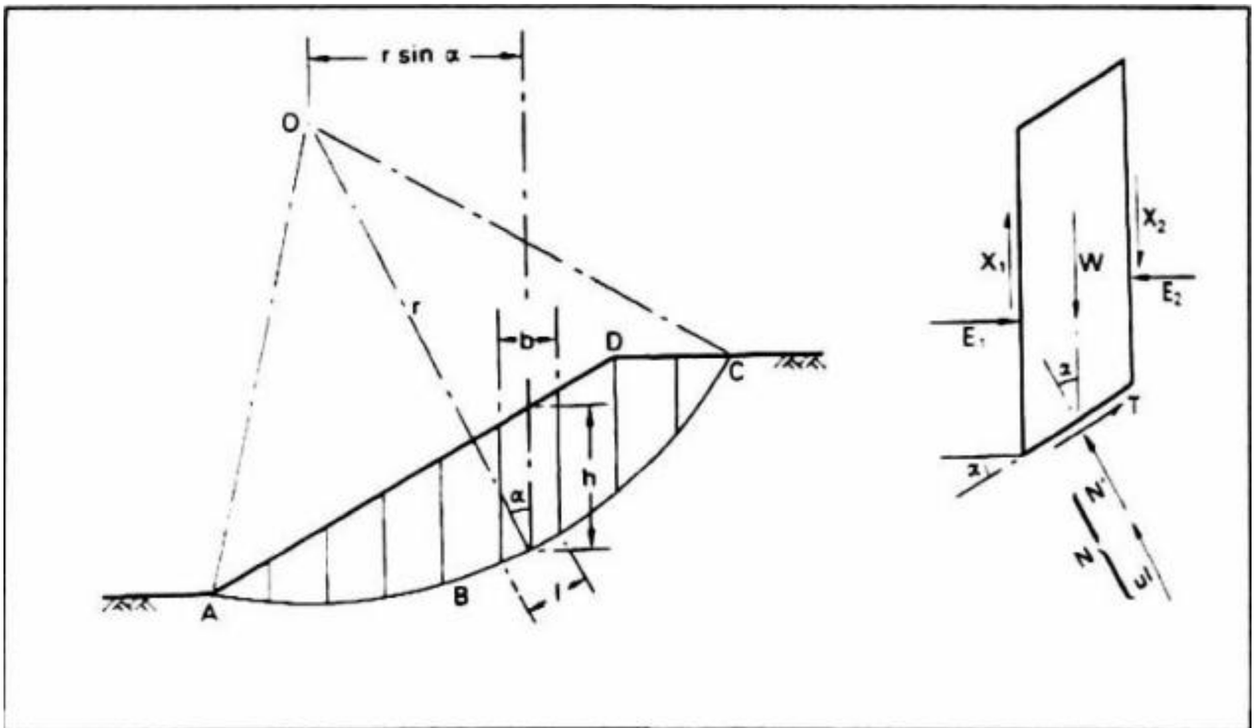

Fig. 3.4 Forces acting on a slice through a sliding mass on a slip surface (Craig,2004)

The definitions of variables in Fig. 3.4 are defined in Table 3.3:

The factor of safety is an important factor in slope design projects. The purpose of the FOS is to account for the uncertainties existing in geotechnical fields, such as the shear strength parameters, hydraulic properties, and any other parameters in ground investigation. It also accounts for the deviations caused by the assumptions and simplifications made from the analysis methods.

The factor of safety can be derived by the summation of slice forces in horizontal and vertical directions and the summation of moments. However, in this problem, the number of unknown variables exceeds the number of known variables, making the problem indeterminate. Proper assumptions on the inter-slice forces (X and E) are required.

Table 2.3Definitions of variables in the free body diagram of a slice(Craig,2004)

Variables	Definitions
W	Total weight of the slice (kN)
T	Shear force on the base (kN)
N'	Effective normal force on the base (kN)
u	Pore-water pressure on the base (kPa)
l	Base length of each slice (m)
N	Total normal force of the slice (kN)
X_1, X_2	Shear forces on the slice (kN)
E_1, E_2	Horizontal inter-slice normal forces (kN)

Duncan (1996) has characterized many methods in a survey of equilibrium analysis, including the ordinary method of slices (Fellenius, 1936), Bishop's Modified Method (Bishop, 1955), Janbu's generalized procedure of slice (Janbu, 1968), Morgenstern and Price's method (Morgenstern and Price, 1965), and Spencer's method (Spencer, 1967). The characteristics of the various equilibrium methods of slope stability analysis are summarized by Duncan and Wright (1980) in Table 2.3.

In the cases of methods satisfying all conditions of equilibrium (e.g. Janbu's Generalized Procedure of Slices; Morgenstern and Price's Method; Spencer's Method); their assumptions induce minimum impact on the value of FOS (Duncan, 1996). Therefore, the last three methods in Table 2.5 provide better accuracy on FOS than the other methods.

Overall, the assumption that the soil mass can be divided into slices, leading to further assumptions on the inter-slice forces, is one of the major features that distinguishes the limit equilibrium method from other methods. However, this is an entirely artificial assumption which may not be correct in the reality. Besides, the assumption made in advance on the shape and location of the failure surface is also relatively subjective.

2.6.3 Finite Element Methods (FEM)

Although limit equilibrium methods have been used for decades in slope stability analyses, the finite element analysis of slopes has drawn the attention of many researchers in recent years as it is able to consider non-linear stress-strain behavior. For example, the elasto-plastic soil models were firstly adopted to assess slope stability by comparing results with traditional methods (Smith and Hobbs, 1974; Zienkiewicz et al., 1975; Griffiths, 1980). Further improvements and subsequent use of the FEM on slope stability analysis has increased confidence in the method (Potts et al., 1990; Matsui and San, 1992; Cai and Ugai, 2004).

2.7 Computer Applications

Slope stability analyses today can be performed by using various computer based geotechnical software. Software utilizing LE (limit equilibrium) formulations has been used for many years. Similarly, finite element (FE) software, based on constitutive laws and appropriate soil models, has drawn growing interest both of researchers and of professionals. Today, both LE and FE based software are commonly used in geotechnical computations.

TABLE 2. 4CHARACTERISTICS OF LIMIT EQUILIBRIUM METHODS (DUNCAN AND WRIGHT, 1980)

Method	Characteristics
Slope Stability Charts (Janbu, 1968)	Accurate enough for many purposes Faster than detailed computer analyses
Ordinary Method of Slices (Fellenius, 1927)	Only for circular slip surfaces Satisfies moment equilibrium Does not satisfy horizontal or vertical force equilibrium
Bishop's Modified Method (Bishop, 1955)	Only for circular slip surfaces Satisfies moment equilibrium Satisfies vertical force equilibrium Does not satisfy horizontal force equilibrium
Force Equilibrium Methods (Lowe and Karafiath, 1960)	Any shape of slip surfaces Do not satisfy moment equilibrium Satisfies both vertical and horizontal force equilibrium
Janbu's Generalized Procedure of Slices (Janbu, 1968)	Any shape of slip surfaces Satisfies all conditions of equilibrium Permits side force locations to be varied More frequent numerical problems than some other methods
Morgenstern and Price's Method (Morgenstern and Price, 1965)	Any shape of slip surfaces Satisfies all conditions of equilibrium Permits side force orientations to be varied
Spencer's Method (Spencer 1967)	Any shape of slip surfaces Satisfied all conditions of equilibrium Side force are assumed to be parallel

2.7.1 Geo-Studio software

Geo-studio 2007 package is an example of a coupled hydrological-slope stability modeling software developed by GEO-SLOPE International Canada, which includes seven products such as SLOPE/W, SEEP/W, SIGMA/W, QUAKE/W TEMP/W, CTRAN/W and VADOSE/W.

The SEEP/W of the Geo-Studio package analyses seepage problems with a numerical discretization technique, whereas SLOPE/W can be used as a limit equilibrium slope stability model. Coupled SEEP/W–SLOPE/W analyses (Krahn2004) can be employed successively to evaluate dynamic stability conditions of embankments and slopes (Rinaldi and Casagli 1999; Crosta and Dal Negro 2003; Rinaldi et al. 2004; Collins and Znidarcic 2004; Dapporto et al. 2005). The results obtained from seepage modeling can be directly linked into SLOPE/W, and it uses a variety of methods to solve problems for the factor of safety.

2.7.1.1 SEEP/W

The flow of water through soil is one of the fundamental processes in geotechnical and geo-environmental engineering. Pore-pressures associated with groundwater flow are of particular concern in geotechnical engineering. That pore-water pressure, whether positive or negative, is an integral component of the stress state within the soil and consequently has a direct bearing on the shear strength and volume change behavior of soil. Research in the last few decades has highlighted the importance of moisture flow dynamics in unsaturated surficial soils as it relates to the design of soil covers.

SEEP/W adopts an implicit numerical solution to solve Darcy's equation for saturated and unsaturated flow conditions, describing pore water pressure and movement patterns within porous materials over space and time. In performing seepage analysis either steady state or transient using SEEP/W, manual of SEEP/W 2007 advises to adopt the following procedures carefully to achieve a reliable output. The first is creating the numerical domain, including the selection of an appropriate geometry and creating the discretized mesh. The second part requires the specification of material properties to the various sub-regions of the domain. The third is the specification of the appropriate boundary conditions. And finally solving and view the results.

SEEP/W is formulated on the basis that the flow of water through both saturated and unsaturated soil follows Darcy's Law

$$\boldsymbol{q = ki} \tag{2.17}$$

Where q is specific discharge, k is hydraulic conductivity and i is the hydraulic gradient. The general governing differential equation for two-dimensional seepage can be expressed as:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial x}\left(k_y \frac{\partial H}{\partial x}\right) + Q = \frac{\partial \theta}{\partial t} \tag{2.18}$$

Where **H** is the total head, $\mathbf{K_x}$is the hydraulic conductivity in the x-direction, $\mathbf{K_y}$is the hydraulic conductivity in the y-direction, **Q** is the applied boundary flux, **θ** is the volumetric water content, and **t** is time.

2.7.1.2 SLOPE/W

Even to this day, stability analyses are by far the most common type of numerical analysis in geotechnical engineering. This is in part because stability is obviously a key issue in any project – will the structure remain stable or collapse? SLOPE/W was the very first geotechnical software product available commercially for analyzing slope stability. Currently, SLOPE/W is being used by thousands of professionals both in education and in practice and it has been designed and developed to be a general software tool for the stability analysis of earth structures. The software SLOPE/W computes FOS for various shear surfaces, for example circular, non-circular and user-defined surfaces (SLOPE/W 20012).

The main steps in analyzing slope stability using SLOPE/W includes

- Geometry – description of the stratigraphy and shapes of potential slip surfaces.
- Soil strength – defining parameters used to describe the soil (material) strength
- Pore-water pressure – means of defining the pore-water pressure conditions.
- Reinforcement or soil-structure interaction – fabric, nails, anchors, piles, walls and so forth.
- Imposed loading – surcharges or dynamic earthquake loads.
- Slip surface – defining the failure surface

SLOPE/W is a limit equilibrium based computer application which computes the factor of safety by utilizing the LE equations discussed in section 3.6.1.

3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1 . Location

The Blue Nile (Abay) Gorge also known as the Africa's Grand Canyon incorporates the National Highway No. 3 GohaTsion – Dejen Road, connecting the capital city Addis Ababa to Bahirdar, Gondar and port of Sudan. It is around 180 km north of the capital, Addis Ababa. It lies in UTM zone 37 with a Geographical extent of ***9°59'58"– 10°10'21" East and 38°4'42" – 38°17'45"***. It has a total area of 456.1 km^2 (JICA interim report,Aprill 2011.

The road is important for transporting agricultural products to the whole country as well as Exporting & importing goods with the neighboring country of Sudan. Thus the relevance of the road is considered high. The Abay river gorge, GohaTsion – Dejen road has a length of 40.6km, from the recent studies (Ex-Post Evaluation of Japanese Grant Aid Project) more than 4.75km is suffered a lot from sliding.

3.1.2. Topography

The Abay Gorge landforms consist of a basaltic lava plateau (Eocene period flood lava), with an elevation of about 2,400 m, and slopes that are dissected by the Abay River. The elevation of the valley bottom at Abay Bridge is 1,060m above mean sea level. The width of the valley is approximately 15 to 20 km at the edge of the lava plateau. The average slope angle from the edge of the lava plateau at the narrowest section is about 9 degrees.

Lateral slopes of Abay Gorge consist of several levels of cliffs, colluvial slopes and denudation slopes. There are seven steps of cliffs observed, and those cliffs are highly resistant to erosion.

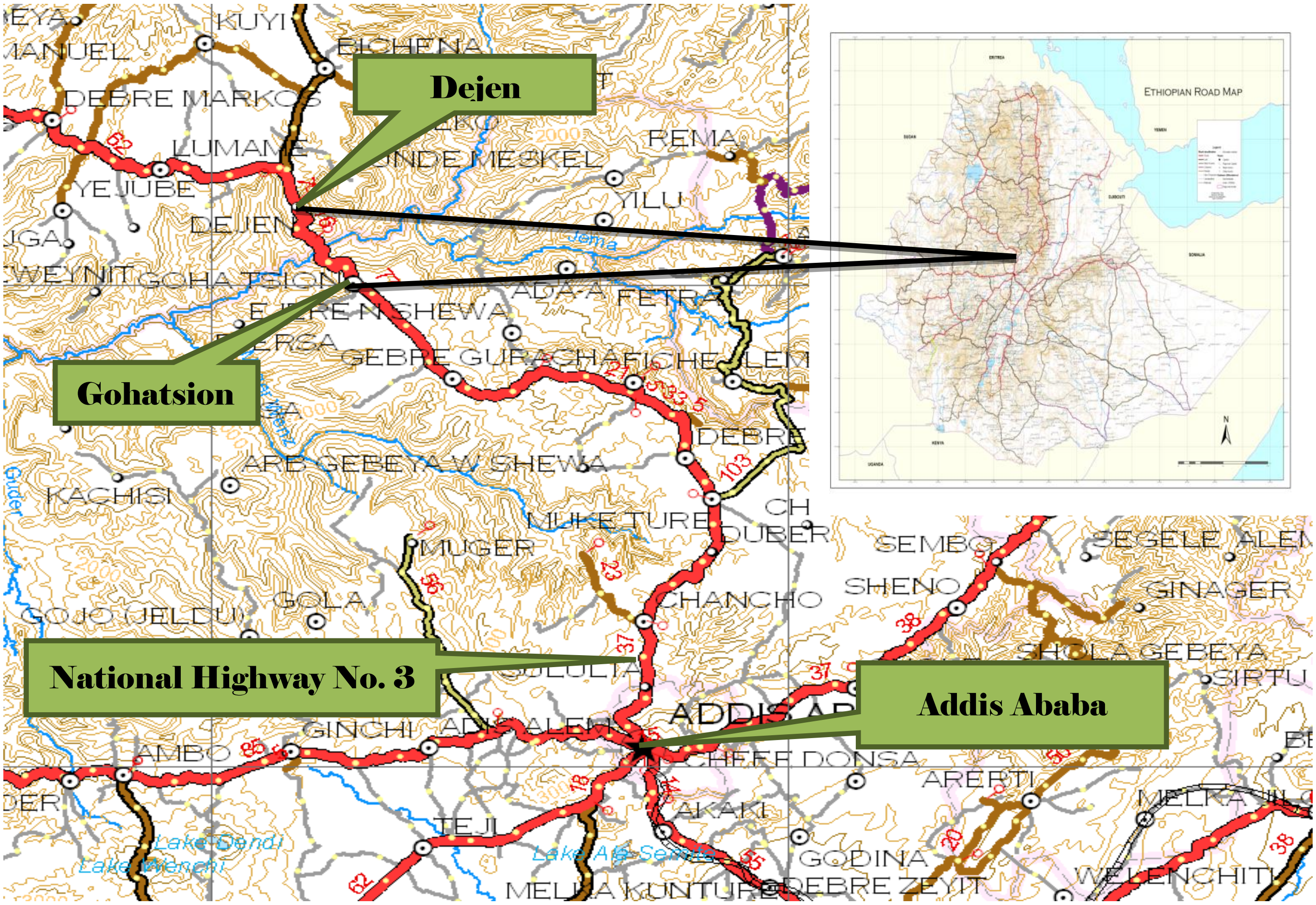

Fig. 3.2 General Location Map of the Study Area (Revised road network ERA, 2010)

Three cliffs at the top consist of basalt lava, three cliffs in the middle consist of limestone and shale, and two cliffs at the lower part of the valley consist of sandstone. Many denudation terraces have been formed above the cliffs.

Very thin soil layers and some debris washed out from the upper slope have deposited on these denudation terraces. At the foot of the cliffs, gentle slopes with fallen rocks from the cliffs form wide colluvial slopes. Though there are a lot of boulders on the slope surface, the size of the debris becomes smaller as the distance from the slope becomes further. Gentle slopes spread out widely mid-way down the Abay Gorge. These gentle slopes develop on the areas of limestone and shale, which are covered by residual soil and colluvial deposits.

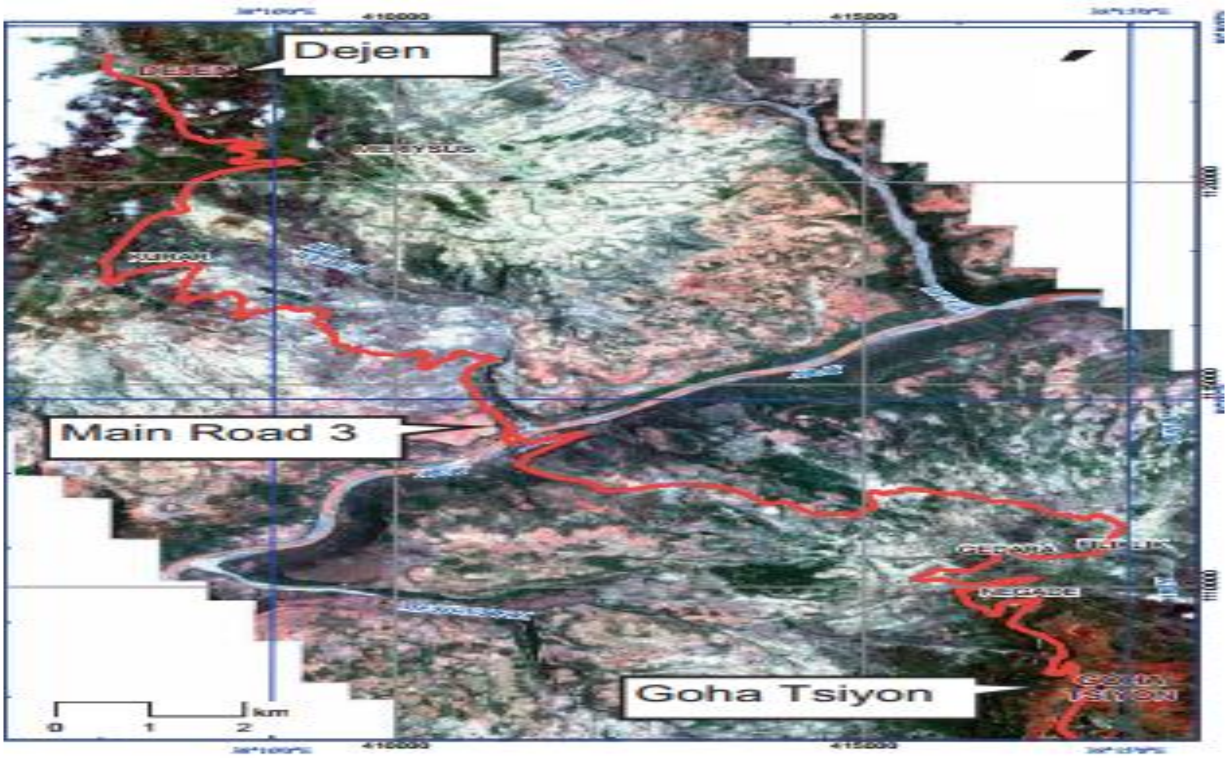

Fig. 3.1 Detailed Location Map of the Study Area(The Project for Rehabilitation of Trunk Road report, 2012)

Several landslides are apparent at these slopes. Major tributaries on the slope of GohaTsiyon side are the Mekentuta River and unnamed river. The Mekentuta River crosses the road at ST.1+150 and flows down in north westerly direction. Several small channels cross the road at Filiklik Village (GSE, 2016 Report).

3.1.3. Climate

3.1.3.1. Rainfall

Ethiopia lies between latitudes 3°00’ to 14°00’ north, and longitudes 33°00’ to 48°00’ east. It is a landlocked country surrounded by five nations (Somalia, Sudan, Kenya, Eritrea, and Djibouti).

Two thirds of the country is alpine, at altitudes over 1,500 m to 4,000 m, and has very steep mountains. The Ethiopian alpine belt could be classified in Koeppen's climate zones (Figure2.3). In a revised version by Trewartha, alp climate (sign H) was added. The alp climate in a low latitude area has a small annual range of temperature, and although it maintains the characteristics of low land tropical climates, the temperature is generally low.

Moreover, it is comparatively cool throughout a year for its latitude. This kind of climate is called "eternal spring.

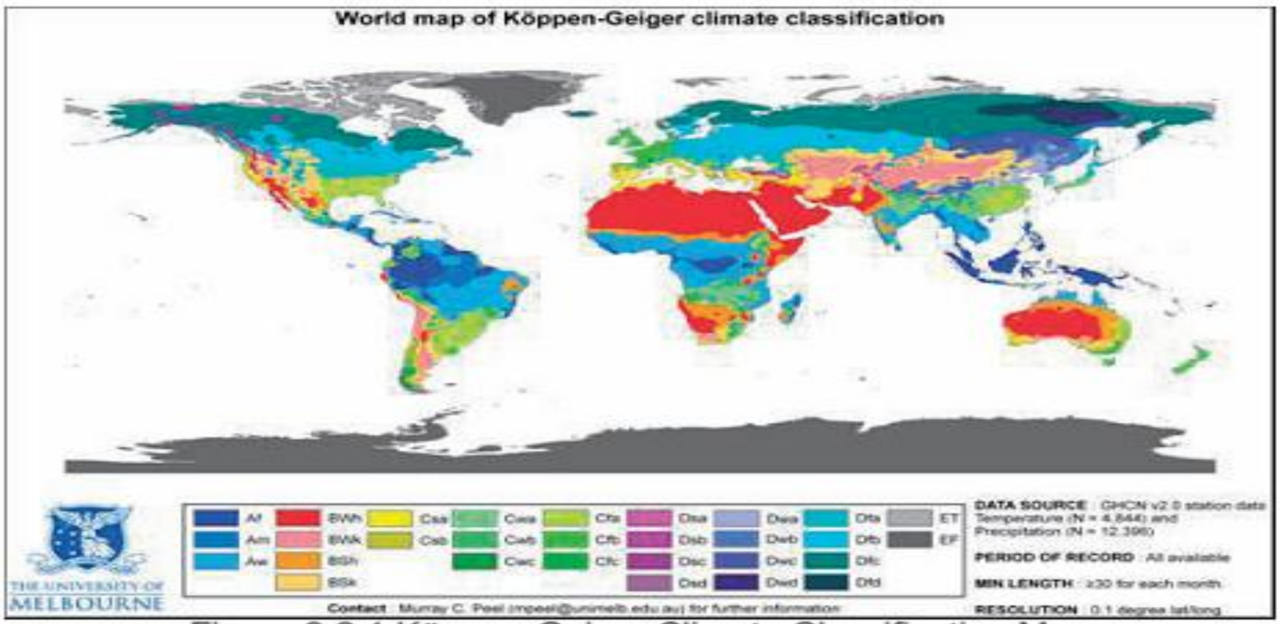

Figure 3.3 Köppen-Geiger Climate Classification Map

Abay Gorge, the target area of the Project, is in the upstream of the world's longest river, Nile, and about 85% of its total volume of water comes from the Blue Nile of Ethiopia.

On the present study, there are about five metrological stations namely GohaTsion, Filiklik, Dejen, Abay-Sheleko/Kurar and Yetnora. The above all observatories are under the jurisdiction of NMSA, which receives observation data, recorded daily at 9 AM, from each observatory on a monthly basis. NMSA manages the collected observation records with a personal computer, and handles their sale and so on. The data management, however, involves insufficient checks, with abnormal values apparent in the records that are possibly measurement mistakes.

The rainy season in the Abay Gorge is from June to September, with July and August accounting for about 50% of annual precipitation.

Existing rainfall observation records in the Abay Gorge area are 49 years and 34 years for Dejen town and Filiklik village respectively and 19 years for Gohatsion, Yetnora and AbaySheleko. In addition, the annual average rainfall is 1,394 and 1,195 mm/year for Dejen and Filiklik respectively. (2016 GSE Report)

TABLE 3. 1 METEOROLOGICAL STATION NEAR ABAY GORGE ALONG GEJEN-GOHATSION TRUNK ROAD (GSE, 2016)

Station name	Latitude (N)	Longitude (E)	Height (m)	Observation
GohaTsiyon	10° 00.408’	38° 14.755’	2,500	rainfall, temperature
Filiklik	10° 03.200’	38° 14.886’	1,860	Ditto
Dejen	10° 10.2638’	38° 09.0359’	2,420	Ditto
AbayShereko	10° 06.7507’	38° 09.4057’	1,819	Ditto
Yetnora	10° 14.696’	38° 14.696’	2,430	rainfall, humidity temperature, radiation, evaporation, wind velocity

3.1.3.2 Temperature

According to the data of WWIS (World Weather Information Service), the temperature in Addis Ababa ranges from a minimum of 15˚C and a maximum 25˚C. The Abay Gorge has an altitude difference of about 1,000 m from its highlands to lowlands. Given the common calculation of temperature change, 0.6˚C to 0.7˚C per 100m, there will be a difference of 6˚C to 7˚C between high and low lands.

3.1.4 Geology

The geology of the Abay Gorge area is characterized by stratified sedimentary rocks capped by basaltic plateau. Figure 2.5 (GSE) indicates a general geological map of Ethiopia. According to Jepson and Athearn (1961) and Tefera et al. (1996), the geology in the area is mainly classified into four formations. Table 2.1.1 shows the table of the geological classification in the area.

TABLE 3. 2 GEOLOGICAL CLASSIFICATION IN THE ABAY GORGE (TEFERA ET AL., 1996)

Era	Name	Geological Descriptions
Tertiary (Paleogene)	Ashangi Formation	Deeply weathered alkaline and transitional basalt flows with rare inter
Jurassic	Antalo Formation	Limestone
	Abay Formation	Middle Jurassic limestone, shale and gypsum
	Adigrat Formation	Triassic to middle Jurassic sandstone

The geological formations in the gorge from oldest at the river bank and youngest at the plateau top are described as follows:

3.1.4.1. Adigrat Formation

This unit represents the upper most part of the clastics beneath the carbonates. It is separated both from the overlying carbonates and the underlying glacial by a sharp rusty unconformity surface.

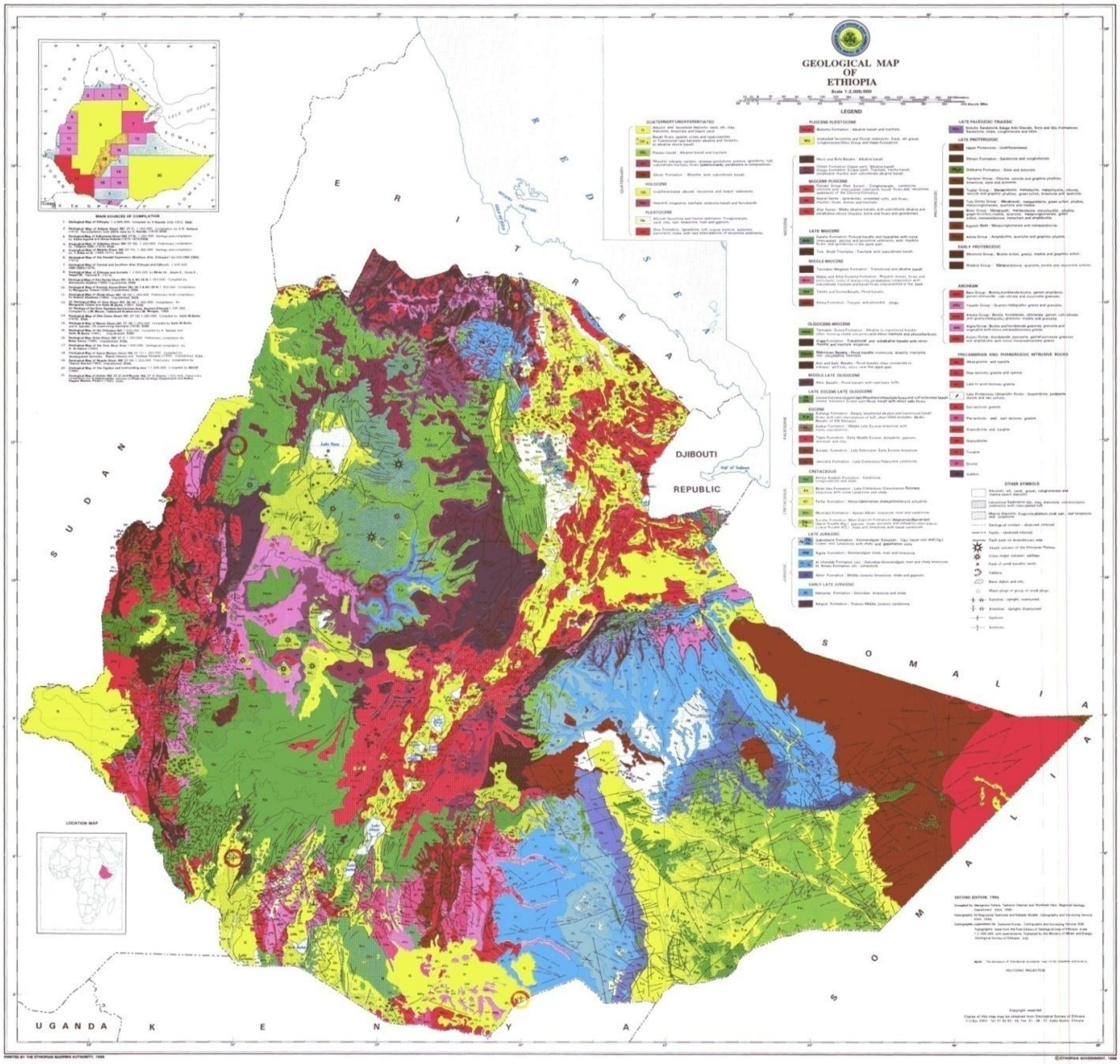

Fig.3.5 General geological map of Ethiopia (GSE, 2016).

In outcrop sections, it is distinct usually by forming vertical cliffs (steep slopes) and reddish brown surfaces. Lithologically, it is typically composed of conglomeratic sandstone with thin, violet colored, commonly massive mudstone beds. The development of other clastic varieties (silt, shale, fine sandstone) is not common. Cross bedding (<30cm bed set thickness) is the very common structure.

Pheno-clasts in the conglomerates are pebble sized quartz, commonly with light grey color. The unit is characterized by typical reddish brown to deep red color and intercalation of violet colored mudstone beds. The alternate succession of cross bedded conglomeratic sandstone and mud implies fluviatile condition. More specifically, the poor development of other sediments than the two may signify a braided stream condition.

3.1.4.2. Abay/Gohatsion Formation

The formation includes variegated shale and fine sandstone inter-bedded with sandy limestone, in its lower part and sandy and silty limestone beds with gypsum layers in its upper part. The occurrence of gypsum layers in association with impure limestone's and shale and fine sandstone units indicates supratidal condition. The clastic in put in the lower part specially may mark a high reach of the supratidal environment. The gypsum layers, as evaporates, explained the prevalence of arid climate during deposition of Gohatsion formation.

3.1.4.3. Antalo Formation

It commonly comprises burrowed limestone and coral and sponge bearing limestone in the lower part and conglomeratic limestone, carbonate shale, bio-turbaned limestone and sandy limestone in the upper part.

The limestones at the lower part are commonly light grey colored and thickly bedded wackstone-grainstone. Antalo Limestone of the study area containing coral and sponge bearing limestone in the lower part and conglomeratic limestone, carbonate shale and impure limestone in the upper part explain the gradual sea level decreasing.

The coral and sponge fragments bearing limestone mark a relatively deeper shallow marine condition. The conglomeratic limestone is formed in intertidal-supratidal environments where the shore line erodes older units and re-cemented the flakes with the newly formed limestone. The fossil ferrous carbonate shale together with its brown color marks a reducing environment, most likely a lagoon with restricted circulation.

3.1.4.4. Ashangi Formation

A series of basaltic flows are observed lying on the sedimentary rocks, uncomfortably. In some places, the lower part of the total succession of the basalts is seen to be separated by oil shale and tuffaceous sediments, and this is considered to be one of major disconformities among the flows. It is dark grey color and aphanitic with thin columnar jointing. McDougal et al, (1975) determined the age of 250m thick equivalent flows at the edge of Abay Gorge along Addis Ababa-Debre-Markos road to range between 27 and 23Ma (Late Oligocene-Early Miocene).

Although the sedimentary and volcanic rocks in the area are exposed largely as symmetrical stratigraphy on both sides of the Abay River, the detailed sequences are unevenly distributed. The sequence in the area is not disturbed due to major faults and is generally horizontally stratified. However, there are a lot of minor normal faults with a down throw of 1-2 meters. Figure 2.3.2 shows a schematic geological cross section of the Abay area (Ayalew and Yamagishi, 2003). The characteristics of the stratigraphy on the major sequences are also described by Almaz and Tadesse (1994).

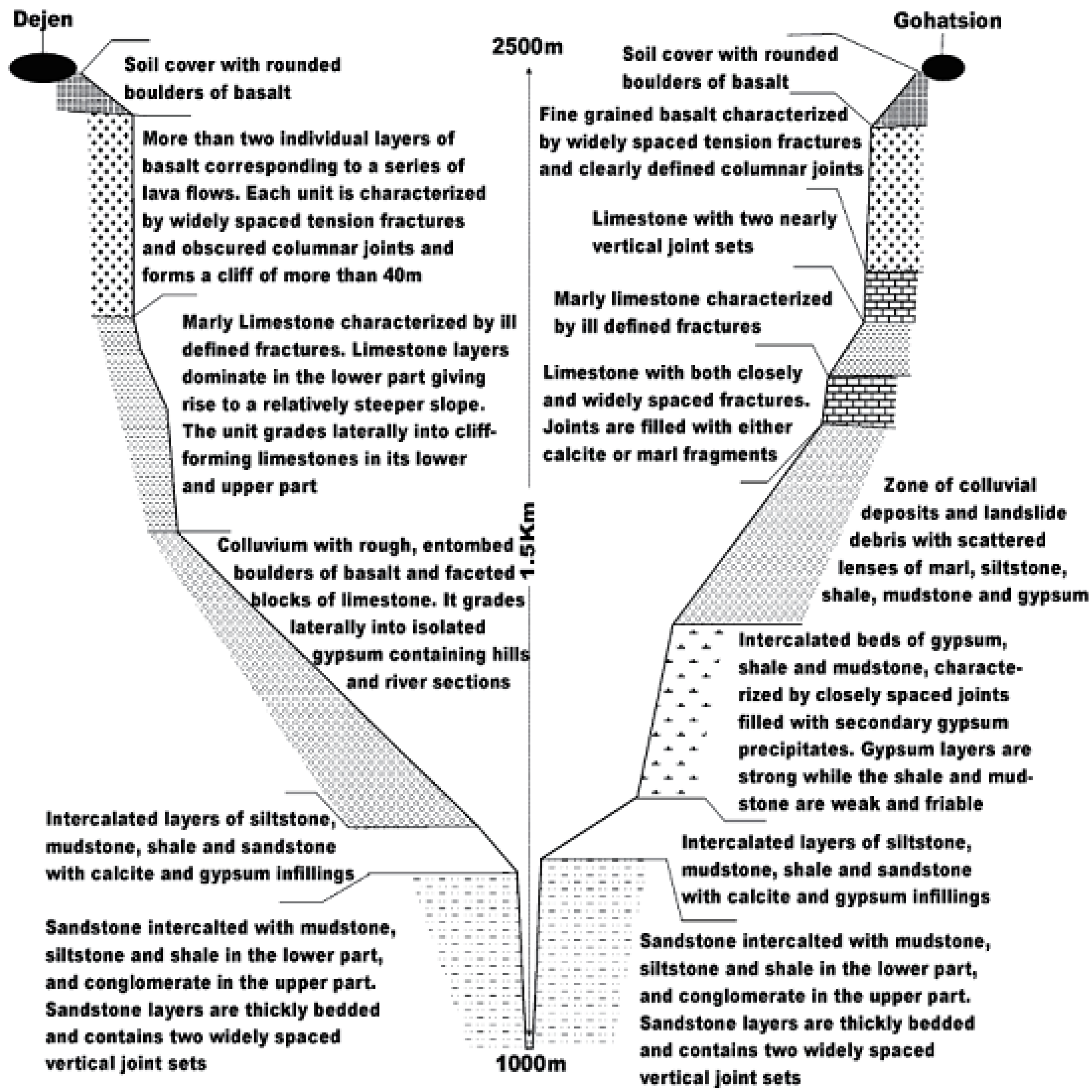

Figure 3.6 Schematic geological section of Abay Gorge (Ayalew and Yamagishi, 2003)

3.1.5. Landslide Problems in the Present Study area

The landslide problem in the present study area is very active. It covers an area more than 300,000 sq. m. The landslide is active and still causing problems in the area. It damages the road and it is still under a risk. There are many tension cracks which are developed in the area, and these tension cracks are indications for probable some more slides to occur in the near future.

According to the local people, after the large landslide, there are always landslides after the end of the rainy seasons, many times, at the beginning of September. Even if the local people could not recognize the exact year, the big landslide took place in the month of September just after the end of the rainy season; the church is even damaged in the beginning of the month of September which is the end of the rainy season. From this we can understand that rainfall is the main cause for the landslide.

According to the local people, historically, the landslide problem in this locality is very recent. It started within the past five years. Just before five years, spring waters started to emanate at different places; tension cracks were developed too before the large landslide problem occurred. Then the massive landslide occurred after a few months later. This landslide causes several problems during and after that time:

- Some people displaced from their home
- Disturbance on agricultural lands – causing damage on the crops as well
- Damage on the road
- Cracks on some houses appeared
- Damage on the gabion wall before a year life time occurred
- Fortunately, there was no injury or life loses due to this landslide problem.

3.2. Methods

3.2.1 Data Collection

Defining the interaction of rainfall and landslide slope failures is categorized among the complex Geotechnical engineering problems which requires detail investigation of the geological, hydrological, morphological characteristics and shear strength parameters of the case study area.

On Gohatsion-Dejen road in Abay Gorge, it hasn't been easy for many researchers to conduct such investigation and analysis on the potential landslide locations due to its geographical location of deep gorge, steep slope and fragile geological condition. Moreover, it is too much expensive to conduct a geological and geotechnical investigation work on individual level.

In this paper data required for landslide stability analysis were collected in two different ways, the first was on site during site visit through observations, interviews, and measurements (Primary data) while the otherwise secondary data which will be obtained from different organization that own & administer the national highway No.3 Gohatsion-Dejen road and companies that made various geophysical investigation works on & around the case study area.

3.2.1.2 Collection of Primary Data

Primary data were collected on site during field visit work and the relevance of collection of primary data for the present study is mandatory for the reason that, in landslide stability analysis proper and intensive site investigation and/or exploration of landslide prone areas has tremendous effect on the reliability of the result of stability analysis.

During site visit, attempts were made to determine and identify the various instability manifestation features present on the slopes and possible data were also collected on site from past landslide slope failures, scarps, tension cracks and presence of springs and streams on and at the toe of the slopes. Besides, efforts were made to identify the extent of damages caused by the landslides on the road, infrastructures and farmlands on the case study area.

Interviewing

Interviewing is one of the methods for data collection about the past events and current landslide situations. During the site visit, informal interviewing of the local people was done to know and understand the history of landslides and damage and causalities arise due to landslide. In the informal interviewing processes different questions were prepared and forwarded for the selected respondents who spend most of their life living or working on the area such as elders, farmer's, religious fathers and technical persons of ERA and GSE.

Field Observations and Measurements

During site visit it is very important to carefully observe and systematically inspect the case study area potential landslide locations and road sections so as to gather sufficient information for the analysis of stability of landslide.

Moreover, due attention and great efforts has been given on the identifying and locating as well as taking measurements of tension cracks, major & minor scraps surfaces, anomalies, springs & streams in addition to damages on the road alignment, farmland and houses.

3.2.2.1 Secondary Data collection

To conduct the required stability analysis on the case study area during rainfall, attempts were made to collect relevant secondary data from published and unpublished reports, journals, articles and past research papers. Moreover, it is also collected from governmental authorities.

For carrying out of the present study, almost all secondary data were collected from ERA which is governmental organization responsible for administration of all national highways in the country and GSE which is also a governmental organization that undertake any kind of geological and geophysical investigation for roads dams and mining industry.

3.2.3 Data Processing

To perform the intended stability analysis of landslide on the present study to the required degree of reliability and adequacy the processing of raw data collected during site visit and from secondary sources into useful forms and inputs for both seepage and stability analysis computer applications has great role.

Accordingly, an enormous effort has been given to the data processing section so as to obtain representative values of different study area's geological conditions, hydrological situation and geotechnical parameters.

Data processing is a post field visit work activity which was done after all necessary data has been collected from various sources. The data processing tasks performed in the present study includes:

- Digitalization of scarps and tension cracks
- Preparation of different topographic maps using GIS, Global Mapper and Auto CAD
- Editing Photographs taken from site visit
- Organizing, cross matching and filtering of data collected from all secondary sources with data obtained from site visit
- Extraction and interpretation of data from various monitoring works such as surface extensometer, inclinometer, and groundwater level reading and borehole extensometer.
- Interpretation of borehole log data obtained from drilling tests.
- Processing of meteorological data specially rainfall data
- Interpretation and extraction of shear strength parameters from all available laboratory tests such as direct shear test.

3.2.4 Selection Methods of potential Landslide Locations

Scrap surfaces and tension cracks are the two basic implication signs of mass movement in any analysis, prediction and hazard mapping of landslides.

From site visit it has been observed that, different scrap surfaces as well as tension cracks were located on various stations along GohaTsion –Dejen trunk road. Those features on the surface of the road, farm land and other infrastructures of the study area indicate the presence of earth mass movement on the area.

Hence, from field observation and measurements as well as secondary data collected from monitoring devices; landslide locations and their possible direction of movement can be located properly on the plan map of the study area.

From a number of potential landslide locations exist on the present study area, selection of potential landslide locations for rainfall induced landslide stability analysis, has been done mainly on availability of geological, topographical, geotechnical and other relevant data and the presence and values of the possible landslide stations on the landslide distribution map and hazard score and risk for road respectively.

3.2.5 Seepage Analysis

In the analysis of landslides and manmade or engineered slope failures, computation of pore water pressures within the soil mass is a fundamental phenomenon, hence, the presence of pore water pressure significantly reduce the effective shear strength of the soil mass and failure may arise due to either the presence of ground water table or due to the infiltration of rain fall down to the ground.

In the present study, seepage analysis has been executed by using finite element computer application called SEEP/W from Geo-Studio 2007

Geotechnical analysis and modeling software. There are two types of seepage analysis conducted in the present study. Steady state seepage analysis is the first stage which aims to determine the initial condition of the slope mass before rainfall occurred and it requires properly defined boundary conditions of the slope section profile. In this analysis a factor of safety also computed in two different ways the difference is being that in one of the analyses the contribution of the negative pore-water pressures was not taken into account.

The aim was to prove that suction distribution within the ground played an important role in keeping the slope mass stable. Secondary data were used as in put for this analysis. The other and most essential type in seepage analysis is the transient, aimed at determining the pore water pressure distribution within the slope mass after rainfall has occurred.

The transient seepage analyses produce a pore-water distribution after rainfall infiltrates in to the soil and this pore water distribution thereby used as in put in slope stability analysis.

3.2.6 Stability Analysis of Landslides

After all of the necessary data has been collected from various sources, and potential landslide slope failure locations has been identified by using collected data during site visit and processing of secondary data, soil profiles along with slope geometry will be defined from geological bore log data and topographic maps respectively. Using the output of seepage analysis which is pore-water pressure distribution, the crucial and most decisive activity in the present study which is the stability analysis of landslide is done.

Stability analysis in the present study has been conducted using a limit equilibrium computer application called SLOPE/W, a package developed by Geo-Studio 2007 international Canada. SLOPE/W provides deterministic analysis and uses limit equilibrium theory to compute the factor of safety of earth and rock slopes. The comprehensive formulation of SLOPE/W makes it possible to easily analyze both simple and complex slope stability problems using a variety of methods to calculate the factor of safety. SLOPE/W has application in the analysis and design for geotechnical, civil, and mining engineering projects.

Finally based on the results of the stability analysis using SLOPE/W, a discussion and conclusion is made on how landslide slope failures will occur after a rainfall event and recommendation is forwarded on remedial measures and for further studies.

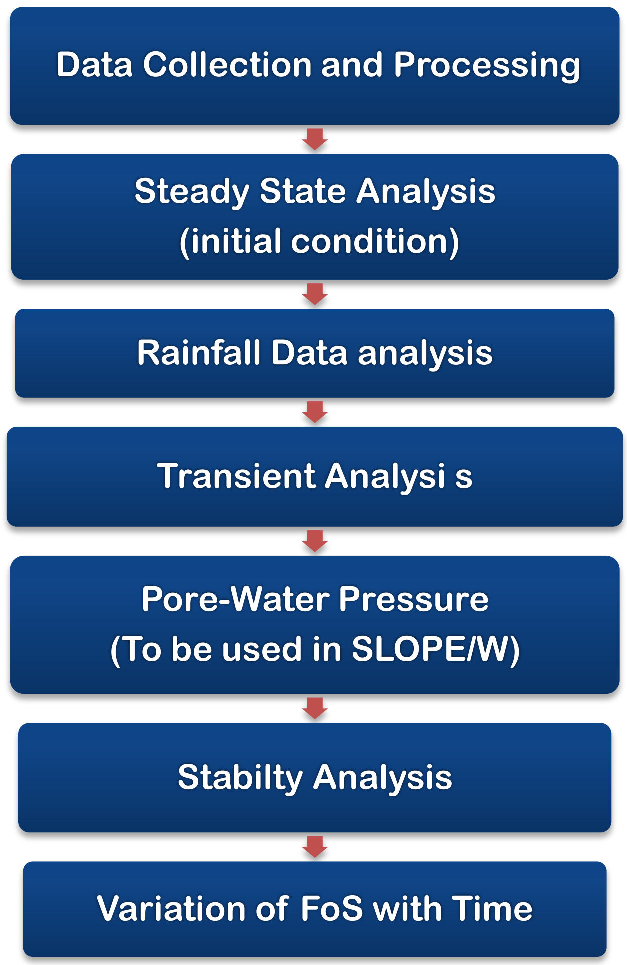

Fig.3.7. Flow chart showing the general methodology of the present study

3.3 Materials

Collection of site specific geological, topographical and geotechnical data; review and study of past landslide slope failures on & around the area; estimating and quantifying of damages to properties, infrastructures and fatalities on both humans and animal due to landslide has a crucial role in stability analysis and prediction and formulation of early warning system of landslides.

Not only collection of data alone is fundamental in landslide analysis, but also sufficient processing and appropriate interpretation of the collected data is mandatory to obtain reliable and more realistic results of the analysis.

Hence, in the present study due attention has been given to processing and preparation of the collected data for the analysis in such a way that, it will represent the site specific conditions.

3.3.1 Data Collected on Site

Site visits were performed on the case study area from Gohatsion to Dejen towns in Abay Gorge. The purpose of the visits was to collect necessary data such as taking measurements on tension cracks, scrap surfaces and collecting soil samples for subsequent laboratory investigations if necessary. The final aim was to use the collected data in slope stability evaluations. In addition, the aim of the visits was to evaluate existing conditions of road section situated at potential landslide locations.

The site visit work has been conducted for 10 successive working days from January 24, 2017 up to February 5, 2017. Data collection during site visit has been conducted in three different but interconnected ways. Those are informal interviewing, site observation and taking of measurements.

Generally during the field work the following data was collected:

- Identification of the type and the distribution of various geotechnical materials forming the slope and the field symptoms of slope distress and movement.
- Major and minor scarp faces, distribution and dimensions of cracks and other damages caused to the infrastructures were observed and recorded.
- The tension cracks and the spring waters that can affect the stability of the slope were also mapped.
- Damages that occurred on the road, agricultural lands and houses because of the landslide process were also recorded.
- Indications or traces for probable future landslide activity were observed and recorded.
- Data about the landslide process by informal interviewing of the local people were also made.

3.3.2.Collected Secondary Data

The necessary data required to conduct the present study are collected mainly from government organization which are responsible for construction and administration of national highways such as ERA, GSE and the EMA as mentioned on the methods section 3.2.

Secondary data for the present study were collected from both offices and published & unpublished sources include:

- Geological Maps
- Topographical Maps
- Borehole log data
- Morphological data
- Geotechnical properties of different materials
- Some Monitoring data and etc.

3.4 Potential landslide location

Referring to successive geological and geophysical investigation work reports conducted by GSE and JICA on Gohatsion – Dejen trunk road, one can easily understand the fact that, most of the road sections are relentlessly suffering from landslide slope failure. As a result, identification of potential landslide prone areas on Abay gorge are not that much difficult with respect to cost and time.

Moreover, a landslide distribution, hazard score and risk for road map (see at the annex) integrated with the topographic data has been obtained from ERA, which was significant in reducing the effort to investigate the landslide prone area and select a possible location for landslide stability evaluation.

However, to carry out the required stability analysis of landslide slope failures due to rainfall events on the road stretch, the availability of the necessary data inputs will generally govern the selection criteria.

Specifically, in this study since conducting field and laboratory tests to determine the subsurface profile and geometry of the slope section as well as to find out the soil parameters which are mandatory for stability analysis requires the involvement of heavy duty machineries (like core drilling) and equipment which thereby demand great deal of money. As a result selection of potential landslide locations and road sections for stability analysis depends on the availability of topographic, bore-log and monitoring data as well as geotechnical parameter determination laboratory test data.

Based on the availability of such data, the values of risk for road and hazard score and the presence on the landslide distribution map as well as the involvement of all possible slope stability scenarios, a potential landslide area located at 10kfrom the Goha-tsion side has been selected for landslide stability analysis induced by rainfall.

3.5 Data preparation and Processing

From both site visit and secondary sources various raw data which are necessary for the execution of landslide analysis has been collected. As a result processing of those raw data in to suitable forms for further analysis of both seepage and slope stability has a crucial on the reliability as well as accuracy of the final result of the stability analysis. Such processing include digitalizing of field measured data such as tension crack depths, preparation of location map of the selected landslide area, preparing couture map of the selected landslide location to define the appropriate geometry, interpretation of bore log and monitoring data.

3.5.1 Topographic data and Maps

The geometry of the slope section to be analyzed, the orientation and aspect of susceptible landslide as well as its extent and damage prediction totally depend on the topographic condition of the area; the need to prepare a topographic map with appropriate scale and reliability for landslide analysis is indisputable.

Beside, in landslide stability analysis, topographic map prepared through topographic surveying on the study area which includes preparing of cross section surveying is useful for the purpose of obtaining base line data for planning the geophysical exploration and monitoring mass movement.

From the topographic map obtained, location map of the selected landslide locations at 10kmfrom Gohatsion town has been prepared including the name and location of boreholes.

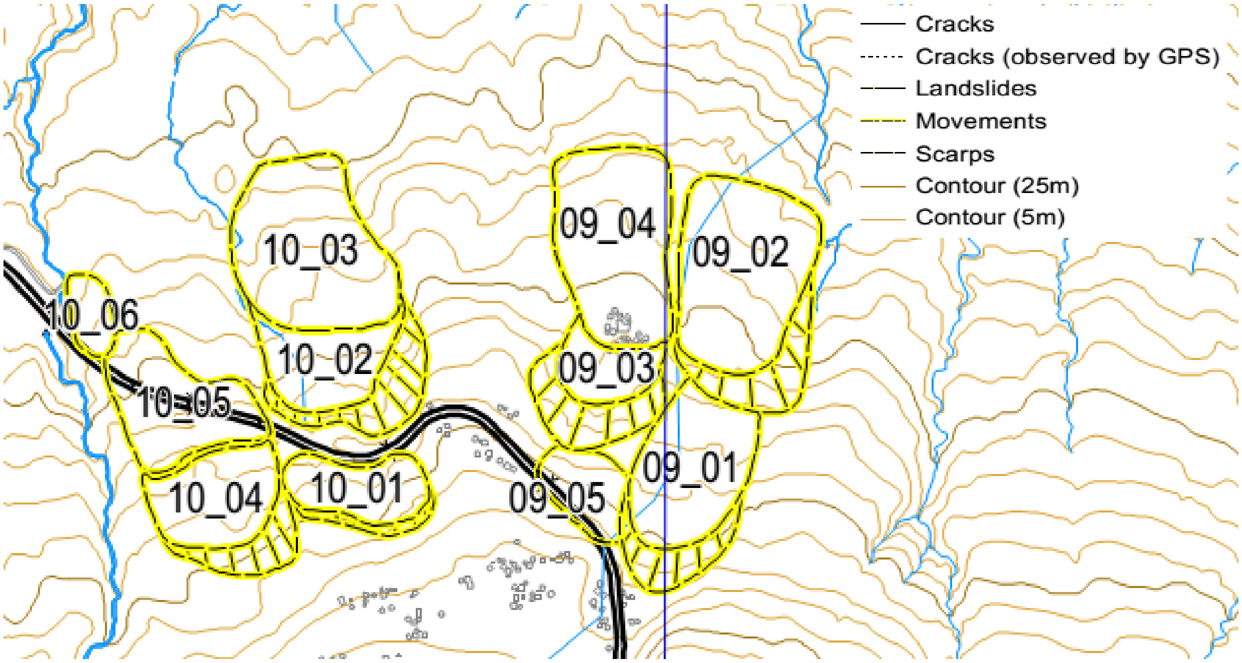

Fig. 3.8 Location map of Landslide at Sta. 10+00km (GSE, 2016)

3.5.2. Geomorphologic data

The selected landslide location is bounded between 4116900- 4174700m E and 1111400-1112230m N. This area exhibit almost the same characteristic with the rest of the slope failure in the Abay gorge. This landslide is differing by its soil cover. The southern part of this land slide has cliff forming colluvial deposit of lime stone with infrequent huge columnar joint of basalt. As well the vegetation cover of the area is sparse.

On the left flunk of the slope failure, there are 2 ponds with in 4m difference. On the other hand new springs are observed. Next to this boundary there is one seasonal river with giant columnar shared basaltic rock falls following the river direction having 6m width, 10m length and >2m depth. On the Right hand side of road from Addis Ababa to Dejen, at the foot of the landslide is small ridge forming limestone. On the Left hand side of the road is also sporadic basaltic boulders with 10 to 30cm width reaching up to more than 1m depth. The lower part of this place is dominantly mixed with fragmented basalt, colluviums of limestone and black cotton soil. Intermittently hummocky terrain is seen on the lower foot of the land slide.

Photo.3.1. Hummocky landform due to instability at station 10Km in the middle part of the landslide.

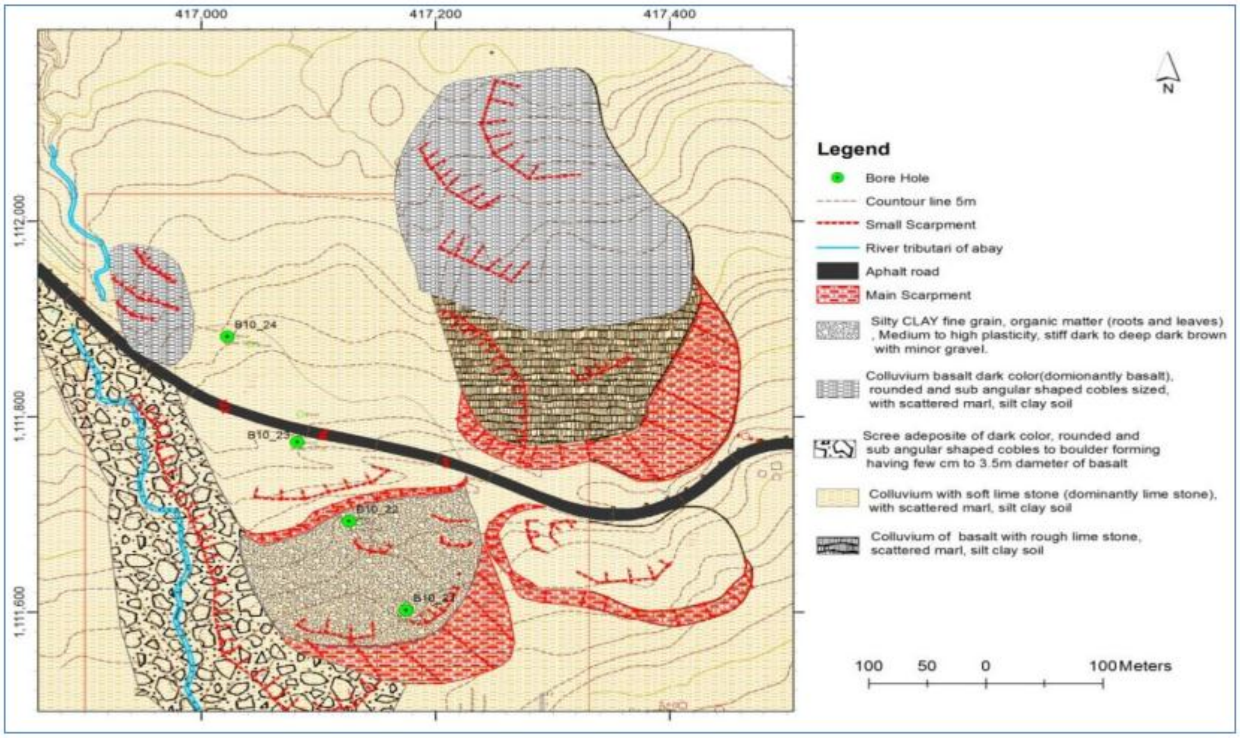

Fig.3.9 Geomorphologic setting of Landslide at Sta. 10+000 (GSE, 2016)

3.5.3. Borehole data

In the study area a number of boreholes are drilled following the road stretch and on agricultural fields. The boreholes were previously drilled by JICA but currently all the drilling survey is undertaken by GSE and it is implemented by taking direct samples from the ground to find the geology and geological structure of each potential landslide prone areas.

In the selected landslide locations both at sta. 10and 26km totally eight boreholes were drilled. BH10-21, 22, 23 & BH10-24 and BH26-21, 22, 23 & BH26-32 were drilled at Sta. 10km and Sta. 26km respectively. The type is core drilling and it covers the road stretch from sta. 10+400 to 10+800 at station 10km. The drilling activity has dual purposes: the first was to conduct logging which aims to define the geological profile of the slope sections;the other was to install monitoring devices. The locations as well as the cross section of boreholes drilled at the selected landslide location are shown below.

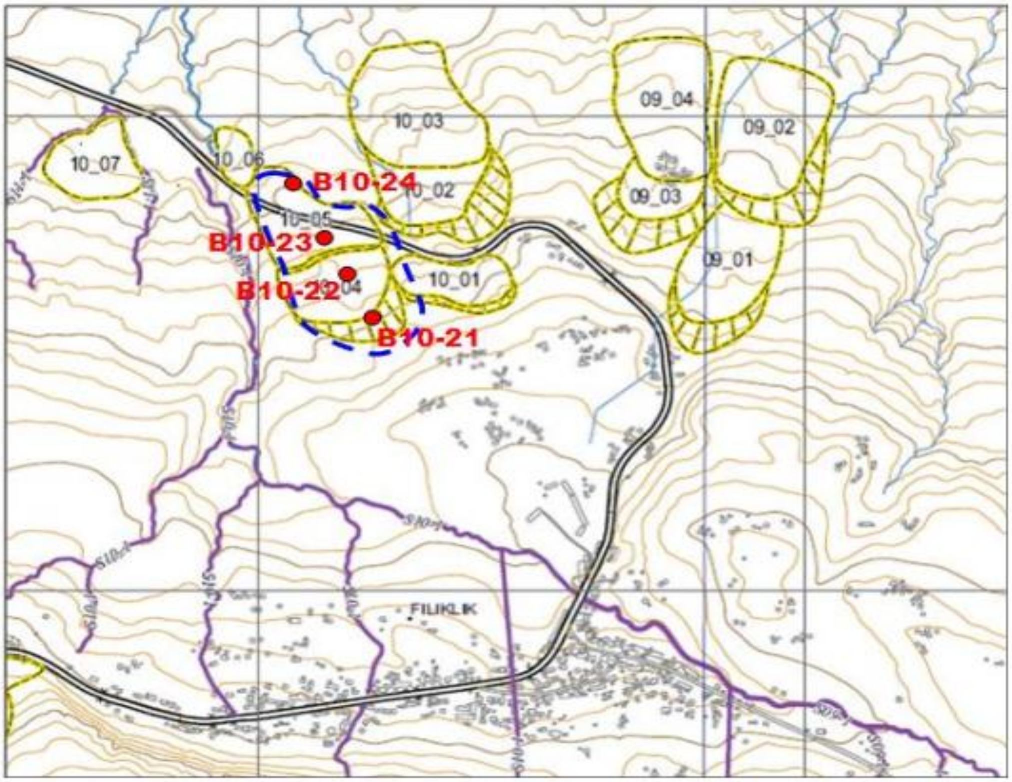

Fig 3.10 Borehole location map of Landslide at 10+00km (GSE, 2016)

3.5.4 Geotechnical conditions and Characterization of engineering parameters

One of the factors that control the instability of a landslide is the type of geotechnical materials in which the landslide is composed of. In order to determine the types and properties of the geotechnical materials exist in the study area a number of boreholes were drilled at different locations as mentioned above and samples taken to conduct tests in the GSE laboratory.

The primary aim of undertaking laboratory tests is to determine and estimate the geotechnical parameters of all soil and rock layers exist on selected potential landslide locations.

The required engineering properties of soils and rock for landslide stability analysis mainly includes, shear strength parameters such as cohesion and friction angle, dry and saturated unit weights.

The GSE geophysical investigation team took representative core rock and soil samples at different depths of drilled boreholes BH10-21, 22, 23 & BH10-21 at Sta. 10km. The samples are tested for direct shear, 1D consolidation and compressive strength determination for underlying rock.

Based on the representative samples taken from the drilled boreholes the selected landslide location for analysis at sat. 10& 26km has modeled as shown in the table below (slope instability investigation and core drilling work report, 2016 by GSE).

TABLE 3. 5MATERIAL MODEL OF SOIL AND ROCK LAYER AT STA. 10KM FOR STABILITY ANALYSIS. (GSE GEOPHYSICAL INVESTIGATION REPORT, 2016)

No.	**Layer Name**	**Friction Angele ø' (°)**	**Cohesion c' (kPa)**	**Unit Weight ɤ (Kg/m³)**
1	Poorly graded Gravel	35.50	0.00	21.00
2	Clayey Gravel	30.00	6.00	20.50
3	Clay	15.00	21.00	18.50
4	Well graded Gravel	38.50	0.00	22.00
5	Limestone	-	-	-

3.5.5. Rainfall data analysis

Rainfall or rainstorm is one of the most significant triggering factors for landslide occurrence. The study of landslide induced mechanics is one of the most important and difficult issues for landslide researches.

In general, the effect of rainfall infiltration on slope could result in changing soil suction and positive pore-pressures, or main water table as well as raising soil unit weight, reducing ant-shear strength of soil and rock.

From the metrological point of view, the month of August is very critical for the study area. Plotting the past 19 years of rainfall days per month at all gauging station reveals that, the month of august has the maximum number of days with rainfalls. Fig.5.6. shows the number of days of rainfall in each month from 1996 to 2015. As a result August has been selected for analysis of stability.

In addition, in order to clearly demonstrate the effect of rainfall duration and intensity, the maximum annual daily rainfall of 84mm/day has been selected and duration of 1-, 2-, and 3-dys and rainfall increment value of 10%, 50% and 100% has been adopted in the seepage and stability analysis.

TABLE 3. 6NUMBER OF DAYS WITH RAIN PER EACH MONTH(GSE GEOPHYSICAL INVESTIGATION REPORT, 2016)

Month	Gohatsion	Fliklik	Abay gorge	Yetnora	Dejen
JAN	1.6	1.6	1.3	2.5	2.6
FEB	1.6	1.6	2.3	2	1.8
MAR	5.1	5.1	1.7	7.6	8
APR	6.4	6.4	5	9.2	10.1
MAY	7.4	7.4	13	8.1	8.8
JUN	14.4	14.4	18.7	17.2	16.7
JUL	26.2	24.9	26.7	27.3	25.1
AUG	24.5	25.2	21.7	24.6	22.9
SEP	11.7	11.7	0	16.7	14.6
OCT	5.7	5.7	2	5.1	7.5
NOV	2.4	2.4	0	1.8	3
DEC	0.9	0.9	1.3	2.6	1.6

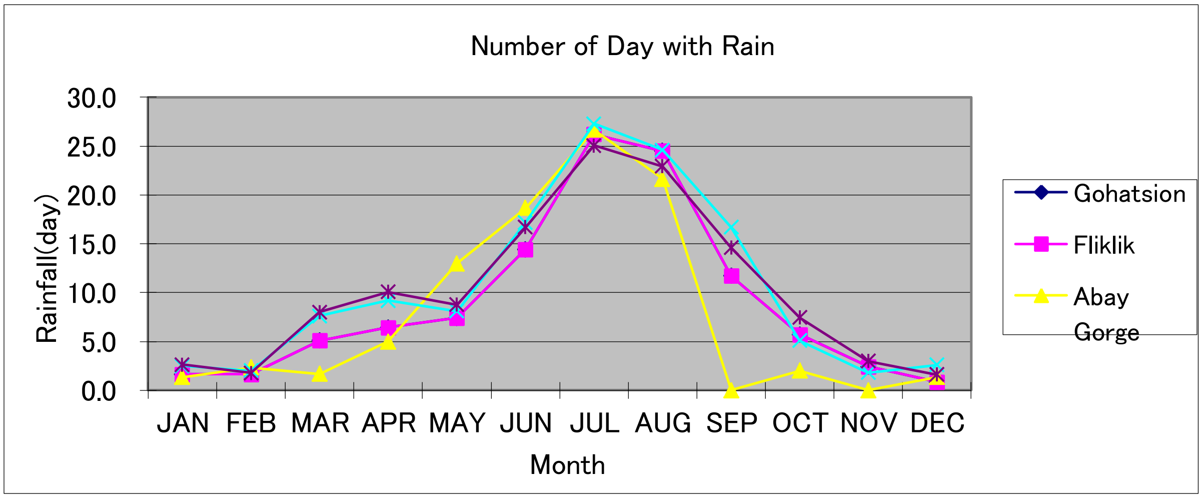

FIG. 3.11 NUMBER DAYS WITH RAINFALL PER MONTH FROM 1996 TO 2015(GSE GEOPHYSICAL INVESTIGATION REPORT, 2016)

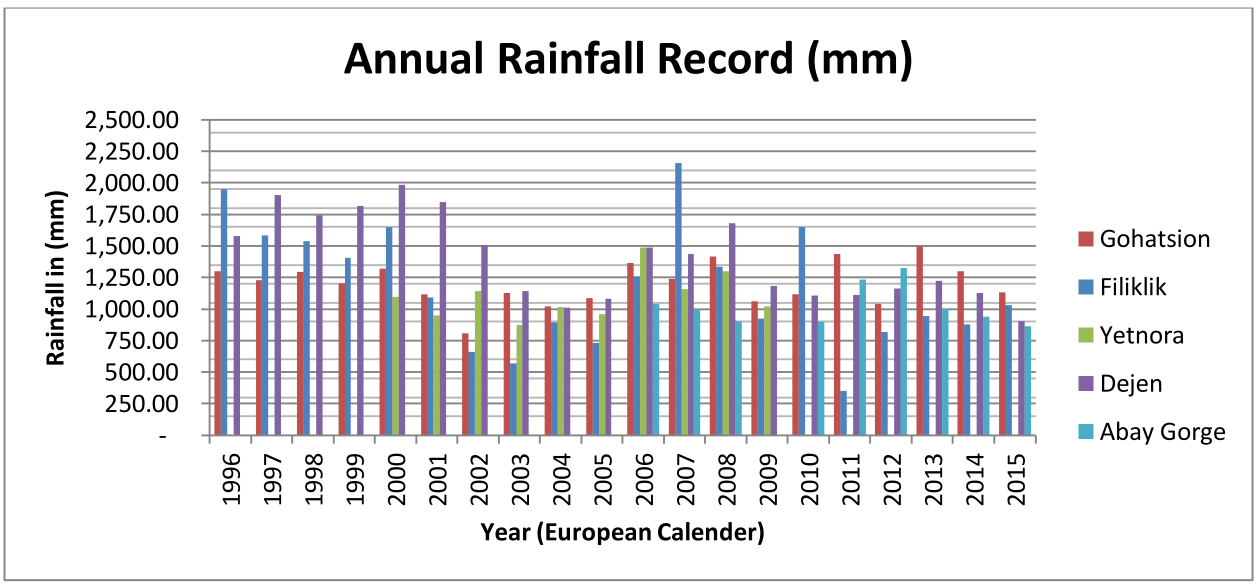

Fig.3.12Annual rainfall at four gauging stations at Abay gorge (GSE, 2016).

4. Stability Analysis

4.1 General

The primary purpose of any slope stability analysis in most engineering applications is to design safe and economical excavations, embankments, earth dams and natural slopes. In each of these structures, the greatest economy may be derived by altering the slope dimensions, which may reduce the FoS. The design of these structures is governed by the minimum factor of safety allowed by the designer. It is thus necessary to have the best possible estimate of the factor of safety.

In the assessment of slopes, engineers primarily use factor of safety values to determine how close or how far slopes are from failure. Conventional limit-equilibrium techniques are the most commonly-used analysis methods. These methods include the Ordinary method of slices; Bishop's modified method, Force Equilibrium methods, Janbu's generalized procedure of slices, Morgenstern and Price's method and Spencer's method. These methods, in general, require the soil mass to be divided into slices. The directions of the forces acting on each slice in the slope are assumed. This assumption has a key role in distinguishing one limit equilibrium method from another.

Limit equilibrium methods require that a continuous surface passes the soil mass. This surface is essential in calculating the minimum FOS against sliding or shear failure.

Among the above all available methods of safety factor computations, the Morgenstern-Price and Spencer methods are selected since, include all inter-slice forces and satisfy all equations of statics.

4.2 Uncertainties in Slope Stability under Rainfall Conditions

Various uncertainties are involved in the stability of slopes affected by rainfall infiltration. First, soil properties that can cause instability of a slope exhibit considerable variation from point to point. The soil properties, e.g. soil permeability, also vary with time because of change of pore-water pressure and stresses. Secondly, when one tries to estimate soil properties from laboratory test results or empirical models, errors in testing and empirical models are introduced into the estimated parameters.

Thirdly, one may also apply a prediction model for slope stability analysis. The uncertainties of the estimated soil properties will influence outcome of the analyses. The intensity, duration and pattern of a rainstorm are not definitely known. The initial pore-water pressures cannot be measured exactly at every point in the slope. The boundary conditions used in the analysis are not certain, even with accurate measurements. Soils are geological materials formed by weathering processes, transported by physical means to their present locations. They have been subject to various stresses, pore fluids, physical and chemical changes. Thus, it is not surprising that the physical properties vary from place to place.

4.3 The Role of Rainfall and Shallow Landslides

It is widely known that rainfall causes to a rise of the groundwater level and a decrease in matric suctions (negative pore water pressures) that results in slope failures. Shallow landslides are one of the most common types of landslides, occurring frequently in steep landscapes in different climatic zones (e.g. Kirkby 1987, Benda and Cundy 1990, Selby 1993).

Rainfall-induced shallow landslides pose a grave threat to human lives and property, since they occur suddenly and often travel along a distance as a high-speed debris flow.

A shallow landslide and subsequent debris flow may cause thousands of deaths and serious economic damage worldwide, especially in mountainous regions subjected to heavy rainfall. Shallow landslides can also be indirectly impacted by climate change, through effects on glaciers, permafrost or forest fires. Glacier retreat and permafrost degradation may lead to large areas of unstable slopes (especially because of cohesion loss, due to the melting of ice particles in these slopes). These voluminous materials could potentially become debris flows at high altitudes, particularly in the case of very steep slopes (Dietrich and Dunne 1978).

4.4 Model Construction

Performing stability analysis of landslide using geotechnical computer application software like Geo-Studio 2007 requires appropriate modeling of the problem. Moreover, the input data used to define and model the problem should be reliable and the appropriate site condition should also be simulated by incorporating the respective input parameters in the software. The proper model development for landslide should include selecting and defining the problem geometry, assigning the appropriate material model and properties followed by applying boundary conditions.

4.4.1 Domain Selection

As previously justified, the selection of the domain for the landslide analysis in Abay gorge was done based on basic and mandatory criteria such as availability of Hydro-geological data since the analysis is a coupled hydrological-stability analysis type. The risks for road and hazard values of landslide locations in the case study area were also the other significant selection criteria.

Hence, the potential landslide location selected in section 4.3 was taken as a domain for the present stability analysis. The plan view and cross-section of the selected domains (sta. 10+00Km) are shown in Fig. 5.1 and 5.2.

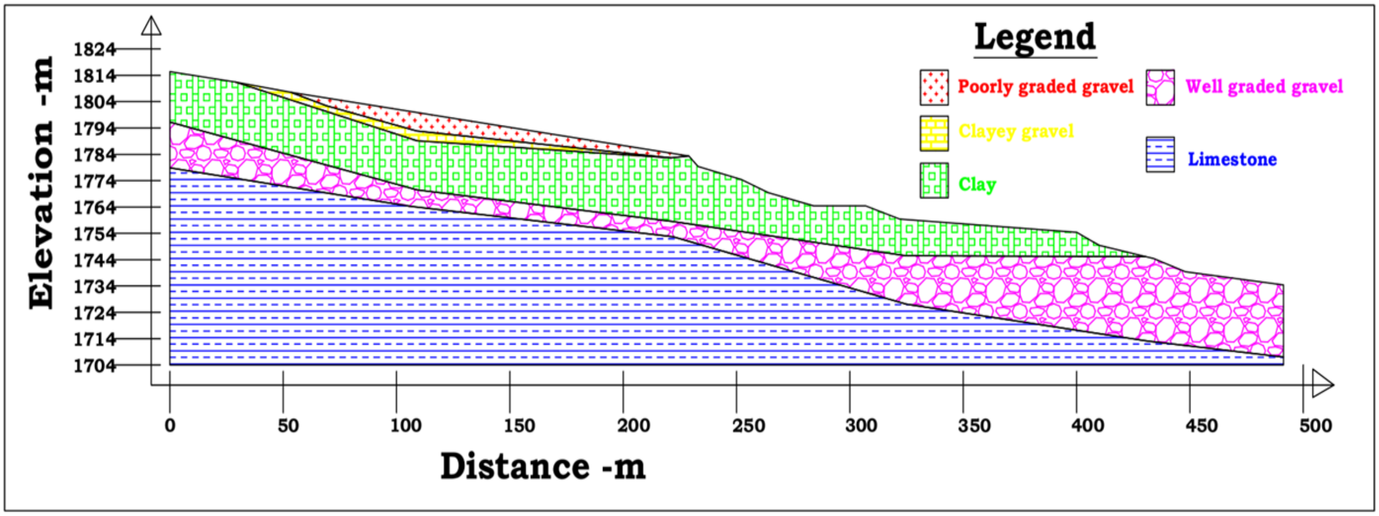

Fig. 4.1 Slope cross-section at sta.10Km

4.4.2 Material Model and Properties

Before commencing the seepage and slope stability analysis using SEEP/W and SLOPE/W respectively, the soil materials of each layer in the potential landslide location of sta. 10Km and 26Km should be modeled properly. Moreover, the appropriate soil properties need to defined by conducting either laboratory or field tests.

In seepage analysis a saturated-unsaturated material model is adopted and the required parameters for proper modeling and simulation of both steady and transient analysis are the water content function and the hydraulic conductivity functions. The water content function describes the ability of the soil to store water under changes of pore-water pressure while the hydraulic conductivity function controls the soil ability to transport water under both saturated and unsaturated conditions.

Table 4. 1Elevations and horizontal locations of soil stratums at Sta. 10Km

Clay	**Distance (m)**	29.0	53.3	109.0	221.1	229.0	229.0	229.1	233.0	252.0
		264.0	284.0	307.0	322.0	400.0	410.0	430.6	324.7	221.7
		109.0	1.7	0.0	0.0					
	Elevation (m)	1812.0	1808.1	1789.7	1783.2	1783.9	1783.9	1783.9	1780.0	1775.0
		1770.0	1765.0	1765.0	1760.0	1755.0	1750.0	1745.7	1746.1	1759.1
		1771.1	1796.4	1796.8	1816.0					
Well Graded Gravel	**Distance (m)**	491.3	491.0	431.3	324.9	222.0	106.1	0.0	0.0	1.7
	Elevation (m)	1707.6	1707.6	1713.7	1727.7	1753.3	1764.8	1779.4	1796.8	1796.4
	Distance (m)	109.0	221.7	324.7	430.6	434.0	448.0	491.3		
	Elevation (m)	1771.1	1759.1	1746.1	1745.7	1745.0	1740.0	1735.0		
Limestone	**Distance -(m)**	0.0	491.3	491.3	431.3	324.9	222.0	106.1	0.0	
	Elevation -(m)	1704.6	1704.6	1707.6	1713.7	1727.7	1753.3	1764.8	1779.4	

In the present study, water content function was estimated from the sample function while Hydraulic conductivity function estimated using Van Genuchten, 1980 method which are available in the Geo-Studio 2007 software package. Both functions are estimated by specifying typical porosity (η) and saturated hydraulic conductivity (K_{sat}) values of each soil layer. Those values of η and K_{sat} are further refined by reviewing and evaluating different literatures, term papers; journals and other internet outputs which has similar geological and hydrological areas.

The saturated water content is taken as equal to porosity on the assumption that all pore spaces will be filled with water during fully saturated condition and the residual water content is taken roughly as 10% of the saturated water content as recommended by SEEP/W 2007 manual.

TABLE 4. 2MATERIAL PROPERTIES FOR SEEPAGE ANALYSIS

No.	Soil Type	Porosity η	Sturated Hydraulic Conductivity K_{sat}(m/s)	Saturated Water Content θ_{sat}	Residual Water Content θ_r
1	Poorly graded Gravel	0.32	4.98*10-2	0.320	0.032
2	Clayey Gravel	0.27	5.02*10-6	0.270	0.027
3	Clay	0.59	1.23*10-7	0.590	0.059
4	Well graded Gravel	0.32	5.01*10-2	0.320	0.032
5	Limestone	0.130	1.1*10-8	0.130	0.013

A Mohr-coulomb material models has been selected to conduct the required rainfall induced landslide stability analysis. The soils parameters used to model the two landslide locations are illustrated in table 5.3.

TABLE 4. 3MATERIAL MODEL OF LANDSLIDE AT STA. 10KM AND 26KM

No.	Soil Type	Friction Angele ø' (°)	Cohesion c' (kPa)	Unit Weight ɤ (Kg/m³)
1	Poorly graded Gravel	35.5	0	21
2	Clayey Gravel	30	6	20.5
3	Clay	15	21	18.5
4	Well graded Gravel	38.50	0	22
5	Limestone	-	-	24

4.4.3. Boundary conditions

Specifying conditions on the boundaries of a problem is one of the key components of a numerical analysis. This is why these types of problems are often referred to as “boundary-valued” problems. Being able to control the conditions on the boundaries is also what makes numerical analyses so powerful.

Solutions to numerical problems are a direct response to the boundary conditions. Without boundary conditions it is not possible to obtain a solution. The boundary conditions are, in essence, the driving force.

As a result boundary conditions in the present analysis are generally defined as a constant head and flux type boundary conditions for both steady and transient seepage analysis.

Constant head type boundary conditions were applied on the right and left boundaries of the problem, while a flux type boundary condition were imposed on the ground surface and soil-bedrock interface of the selected potential landslide locations at sta. 10Km. The boundary conditions applied on the up and downslope section at 10km station is 1816m and 135m respectively.

A flux equal to the saturated hydraulic conductivity of limestone was assigned to the soil bedrock interface as a boundary condition on both stations.

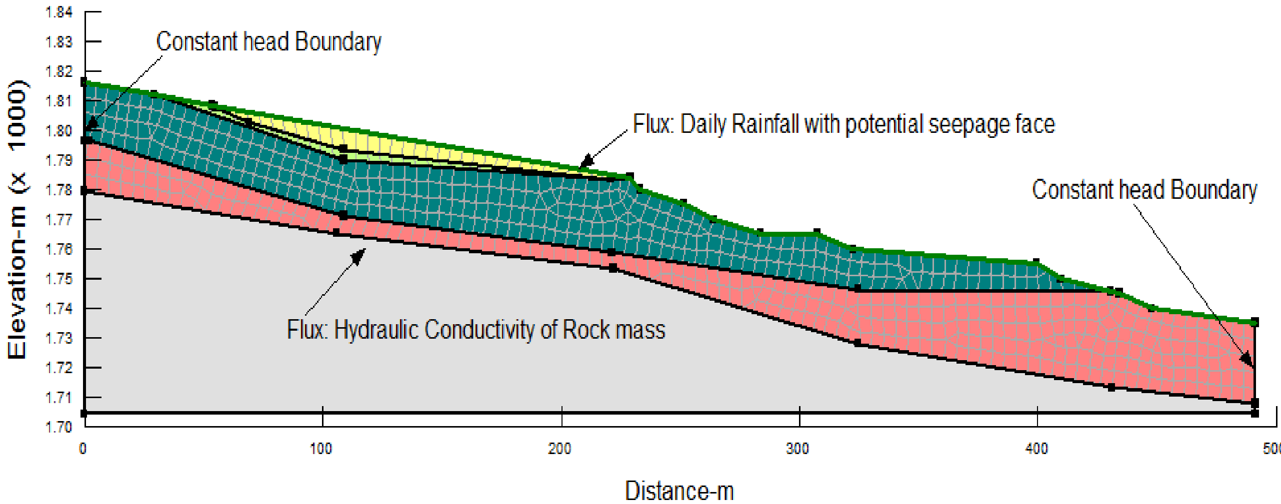

Fig.4.2.Configuration of 10Km Landslide Model and Boundary conditions.

Regarding to the rainfall, as previously outlined August is the critical month; hence, from the past 19 years available daily rainfall data, a year with highest average rainfall of August has been selected for clearly demonstrate the distribution of pore-water pressure distribution as well as factor of safety values throughout the month, which is 2008 at Filiklik metrological station for the 10km sta. landslide analysis.

Moreover, in order to investigate the relationship between rainfall duration and slope stability, annual maximum daily rainfall 84mm/day at Filiklik gauging station with duration of 1day, 2days and 3days has been selected for analysis at 10Km Sta. The variation of pore-water pressure and factor of safety for intensity of 10%, 50% and 100% of the annual maximum daily rainfall also demonstrated in the present study.

4.4.4. Mesh and time step

Finite element numerical methods are based on the concept of subdividing of a continuum into smaller pieces, describing the behavior or actions of the individual pieces and reconnecting all pieces to represent the behavior of the continuum as a whole, this process of the continuum in to smaller pieces is called discretization of meshing and the pieces are known as finite elements.

In numerical analysis as the mesh size gets finer and finer the accuracy of the result increase while the time of simulation and analysis increase and vise versa. To avoid such disadvantage selecting optimal size of mesh is necessary.

In the present study, a mesh size of 2.5m by 2.5m has been selected for station 10km slope sections due to the fact that, the geometrical section are very large.

Regarding to time stepping for the transient analysis an exponential type with a time step of 1day and a total of 31days for the whole month of august has been selected at 10Km sta. to simulate the critical month.

5. Results and Discussion

5.1. General

The landslide stability at station 10Km on Gohatsion-Dejen trunk road in the Abay Gorge due to rainfall, were analyzed for different conditions and rainfall scenarios. Seepage analysis was done using SEEP/W a FE software to compute the pore water distribution within the slope mass both at steady state and transient due to rainfall. And stability analysis was conducted by a limit equilibrium based computer application, SLOPE/W which directly uses the computed pore-water pressures distribution results from SEEP/W.

Stability analysis was done first for the critical month of August, which has the highest number of rainfall days in the past 19 year's rainfall data, by adopting the daily rainfall distribution in the month at Filiklik gauging station.

The effect of variation of rainfall duration and intensity on Pore-water pressure distribution and FoS variation were also computed by analyzing the 10Km sta. potential landslide location for 1-, 2-, and 3-day rainfall duration and 10%, 50%, and 100% increment of the intensity of maximum daily rainfall of 84mm/day respectively.

The stability analysis was done by using the shear strength parameters obtained from field and laboratory test conducted by the geophysical investigation team of GSE as reported Geophysical investigation report (2016).

The section at which the all soil layers incorporated which is 125m from the upslope was selected and all pore-water pressure distributions in both steady and transient analysis are displayed at this section.

5.2. Seepage Analysis Result

5.2.1. Steady state (Initial condition)

In order to demonstrate the effect of rainfall on the 10Km sta. potential landslide location on the Gohatsion-Dejen Road, the Initial condition was analyzed by assuming the dry period with no rainfall just before the rainy season.

During the steady state seepage analysis the boundary conditions are as discussed in section 5.4.3., but in order to simulate the effect of infiltration capacity of the limestone bedrock, a unit flux boundary condition equal to the permeability of the limestone is applied along the soil-rock interface was applied and the seepage analysis result from SEEP/W is shown below.

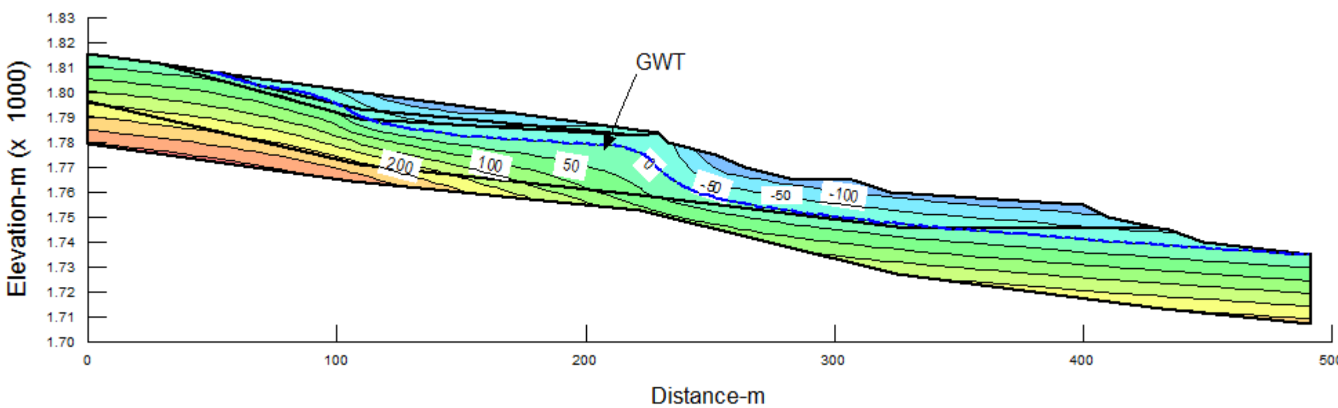

Fig.5.1. Steady state seepage analysis pore-water pressure distribution

The profile at 125m section from the up slope shows that, the GWT is located at an elevation of 1799m a.m.s.l. which is nearly 9.8m deep and the suction at the ground surface was found to -117.3kPa.

In order to validate the computed pore-water pressures from SEEP/W field measurement of GWT levels and negative pore water pressure is mandatory. However, in the present study due to the lack of measured suction and piezo-metric level reading data, it is difficult to conduct verification of the model result.

As a result, only simulation of seepage and stability analysis of potential landslide due to rainfall infiltration at 10Km station was conducted.

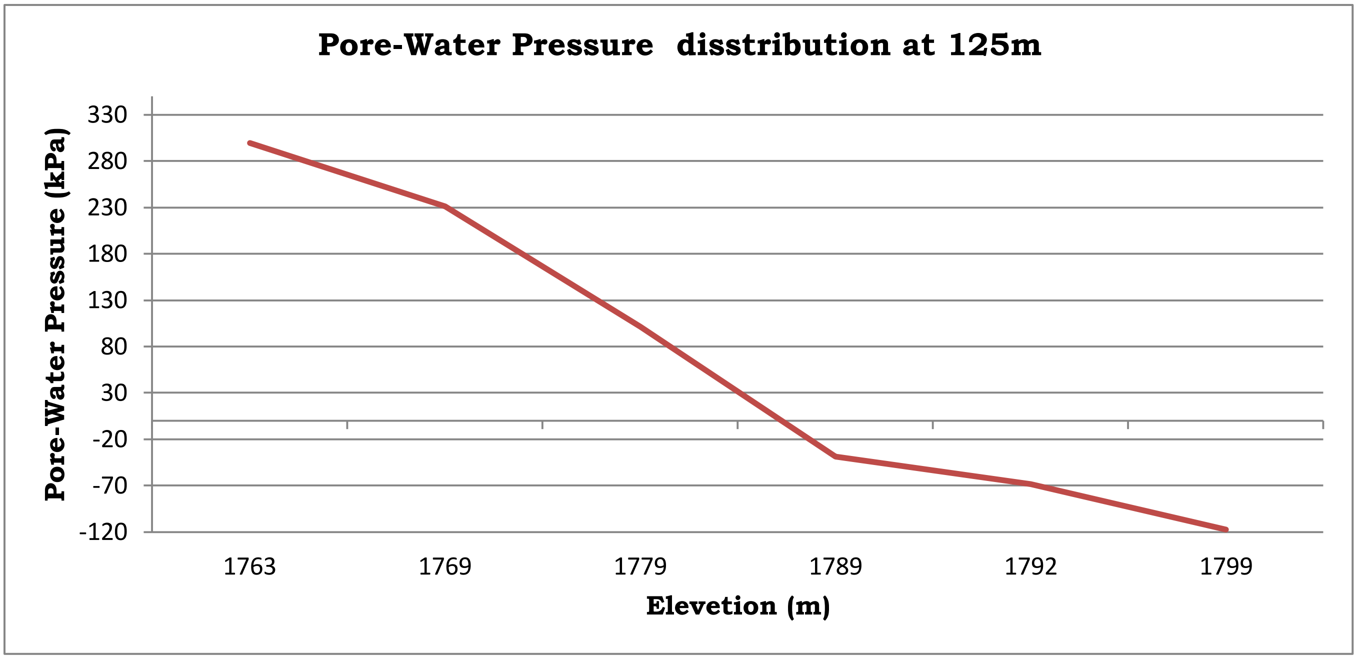

Fig.5.2.Steady state Pore-water pressure distribution at section 125m

5.2.2. Transient Seepage Analysis Result

To ultimately simulate the transient seepage analysis at 10Km sta. potential landslide location due to rainfall in wet season, this study computes the pore-water pressure distribution for the following scenarios: [1] for critical month in the year (August) for the duration of 31days using the daily rainfall as surface flux function, [2] for rainfall durations of 1-, 2-, and 3-days using the maximum daily rainfall intensity of 84mm/day and [3] for rainfall intensities of 10%, 50% and 100% increments of the maximum daily rainfall for duration of 1-day.

5.4.3.1. Critical monthPore-water pressure distribution

During the month of august, which has highest number of days with rainfall, from SEEP/W result the general pore water pressure distribution at 125m section as shown in figure below reveals that, the site responds with high values of positive pore-water pressure during high rainfall days and high values of suction were observed on the days of null rainfall.

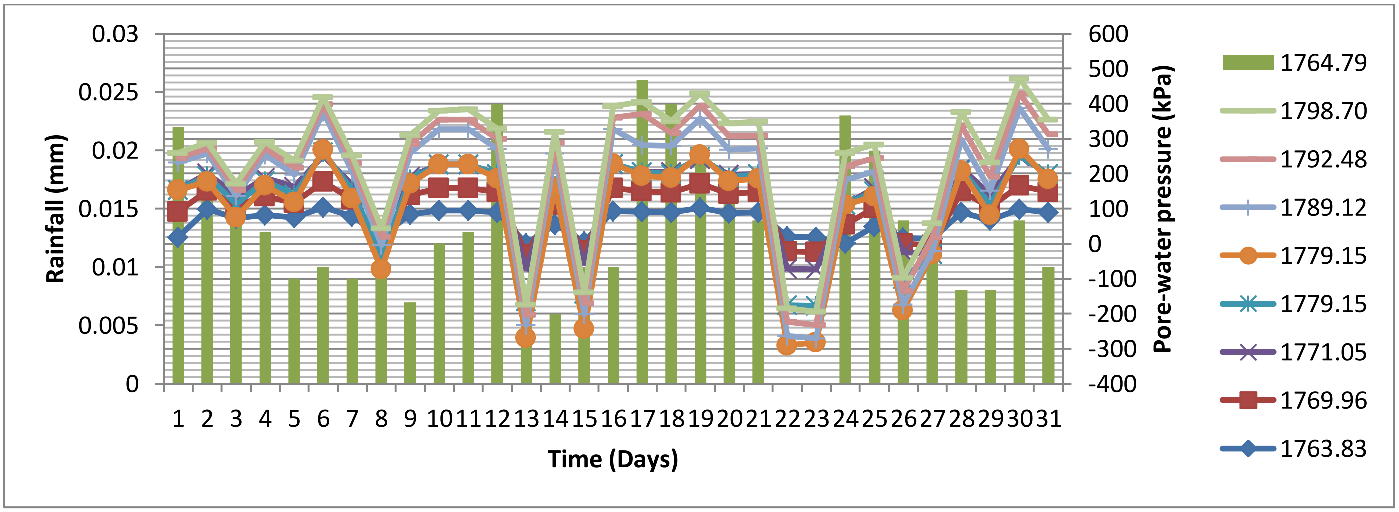

Fig.5.3. Pore-water pressure distribution at 10Km Station during the critical month

For instance, on the days of high rainfall such as 12th, 17th and 24th of August 2007, the pore-water pressure values were 29.4kPa, 35kPa and 38.2kPa respectively. While on the days of null rainfall on 22nd and 23rd August, 2007 as shown in the graph, the pore-water pressure drops dramatically from the previous rainfall days and reach as low as -115kPa and -104kPa respectively.

Generally from figure 5.3., it can be said that, the variation in pore-water pressure at 10Km sta. landslide during the critical month of August shows similar fashion as the daily variation in rainfall.

Moreover, from the analysis result it can also be noted that, the development of pore-water pressure was usually transient due to high permeability of the upper soils and potential seepage face on slope. The location of GWT in all day's simulation varies and temporary saturated zones (perched water tables) developed with in the soil stratum.

5.4.3.2. Seepage field and Rainfall duration

Duration of rainfall has considerable effect on the seepage field of a given slope section. At certain rainfall intensity, long duration allows large amount of precipitation infiltration into landslide, while short duration shows the opposite. Apparently as the rainfall duration gets larger, the landslide becomes less stable.

In transient seepage analysis at 10Km sta. landslide using SEEP/W, a rainfall intensity equal to the annual maximum daily rainfall of 84mm/day from the available 19 years rainfall data at Fililik gauging station were adopted for 1-, 2-, and 3-days duration.

The result of transient seepage analysis at the potential landslide location for the critical period of the end of the rainfall duration can be seen in the figures from fig.6.4 to fig.6.5.

From the result it can be said that, with prolonged rainfall duration, the three conditions tend to create transient saturated state and pore-water pressure rise zone along the slope surface, since the slope is affected by different rainfall durations. As a result, the area and shape of perched water tables (temporary saturated zones) increases considerably.

At the same rainfall intensity of 84mm/day, the generated temporary saturated zone is larger in 3-day rainfall duration than 2- and 1-day durations. This due to the fact that, when the rainfall duration prolongs the total amount of rainfall water in the interior slope arises significantly as the slope can maintain infiltrated precipitation at the speed of saturation infiltration rate, resulting in the increase in temporary saturated zones and pore-water pressure regions.

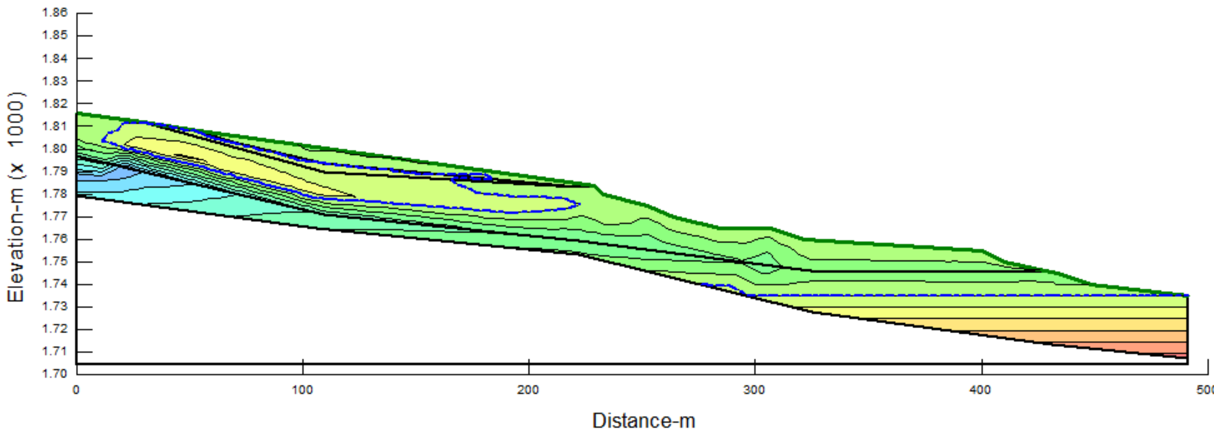

Fig.5.4. pore-water distribution of 84mm/day rainfall after 1-day duration

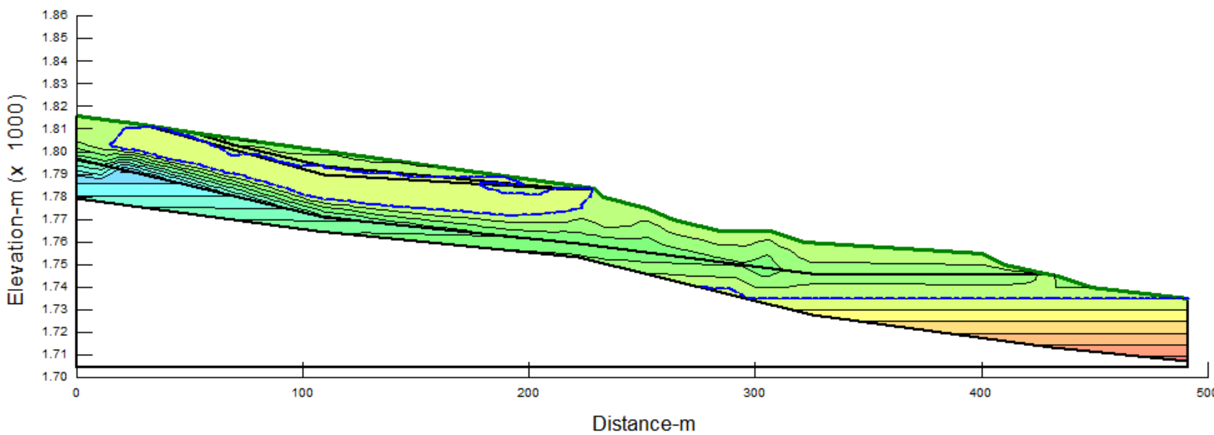

Fig.5.5. pore-water distribution of 84mm/day rainfall after 2-day duration

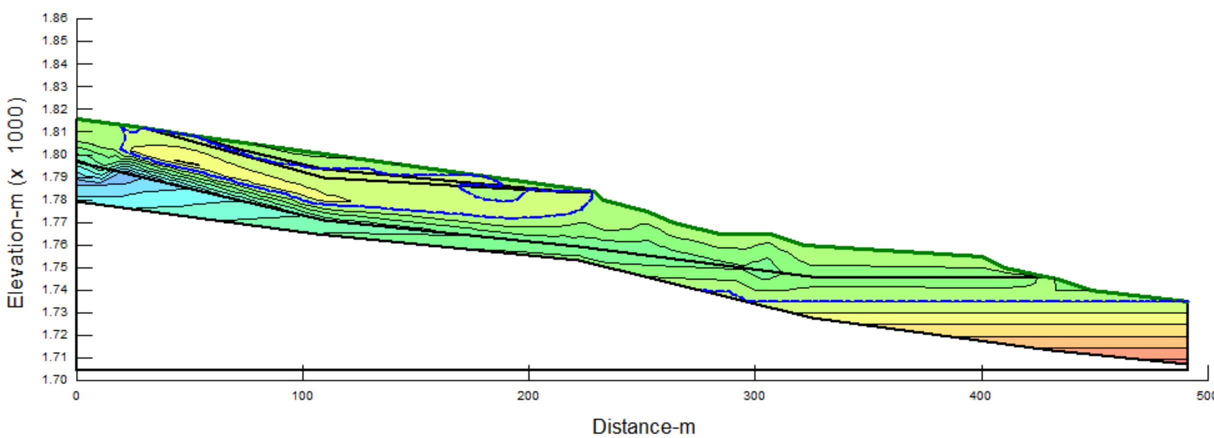

Fig.5.6. pore-water distribution of 84mm/day rainfall after 3-day duration

5.4.3.3. Seepage field and Rainfall Intensity

In the present study, to clearly demonstrate the effect of rainfall intensity in the pre-water pressure variation at 10Km sta. landslide, seepage analysis was examined under 10%, 50% and 100% increment of the maximum daily rainfall of 84mm/day at Filiklik gauging station near to the site for one day duration, which are 92, 126, and 168mm/days respectively .

In order to grasp the idea behind the variation of suction during the application of 92, 126, and 168mm/days of rainfall intensity, it is useful to look at the rate of change of matric suction of the slope section at 125m from upslope.

During the 10% increment of the rainfall intensity, the rate of change of suction was on average -2.7kPa per half an hour from its initial value of -117.6kPa. While as the rainfall intensity becomes 126mm/day, the change in negative pore-pressure increased into -4.77kPa and the total suction gets -112.8kPa. -7.8kPa suction reduction over half an hour has been observed, when the rainfall intensity increment on the maximum daily rainfall becomes 100%, which is 168mm/day.

Hence, it can be seen from the analysis result that, as the rainfall intensity gets larger the dissipation of matric suction becomes faster and faster.

5.5. Stability analysis result

The factor of safety of the potential landslide location at 10km sta. was computed using Mongenstron-Price method, since it satisfies both moment and force equilibriums.

The geotechnical parameters considered for the analysis are already reported in table 5.4. In each simulation models an auto locate type critical slip surface determination method was adopted. Moreover, the stability analysis critical slip surfaces were optimized with 2,000 maximum number of iteration.

Landslide stability analysis at 10km sta. of Gohatsion-Dejen road, conducted for both steady state (dry period) and transient state (rainy season).

5.5.1. Initial condition

The factor of safety of the potential landslide location at the end of dry period i.e. initial condition, was calculated by importing the pore-water pressure distribution computed at steady state directly from SEEP/W in to SLOPE/W, in two different ways the difference is being that in one of the analysis the contribution of the negative pore-water pressure was not considered.

The aim was to prove that suction distribution within the slope mass played an important role in keeping the 10km sta. landslide stable. In SLOPE/W if $\boldsymbol{\phi^b}$is undefined, any negative pore pressure is ignored. However, if a non-zero value of Φ^b is specified, SLOPE/W adds the extra component dependent on suction to the slice base shear strength and computes the FoS.

As a result, when the suction were not considered ($\boldsymbol{\phi^b}$= 0) the FoS was found to be 1.394. However, when the suction was in the stability calculation the FoS was 1.506.

The result conform the importance of negative pore-water pressure on the stability of landslide at station 10Km from Gohatsion town.

5.5.2. Stability in the Critical Month

The month of August in the Abay gorge has the highest number of days with rainfall among other months in the past 19 years, as per the recorded rainfall data from NMAE. More than 25 days on average has rainfall in august. Referring the month in which the stability analysis was done, only two days has no rainfall the rest 29 days received a rainfall ranging from minimum of 6mm to maximum of 26mm.

Hence, the stability analysis was carried out for each day of the month of August 2007 including the null rainfall days, in order to clearly demonstrate the effect of rainfall in triggering landslide. The optimized slip surfaces were estimated for each model for the month of August. The optimized critical slip surface FoS values and the daily rainfall of August 2008 is illustrated in fig. 6.7.

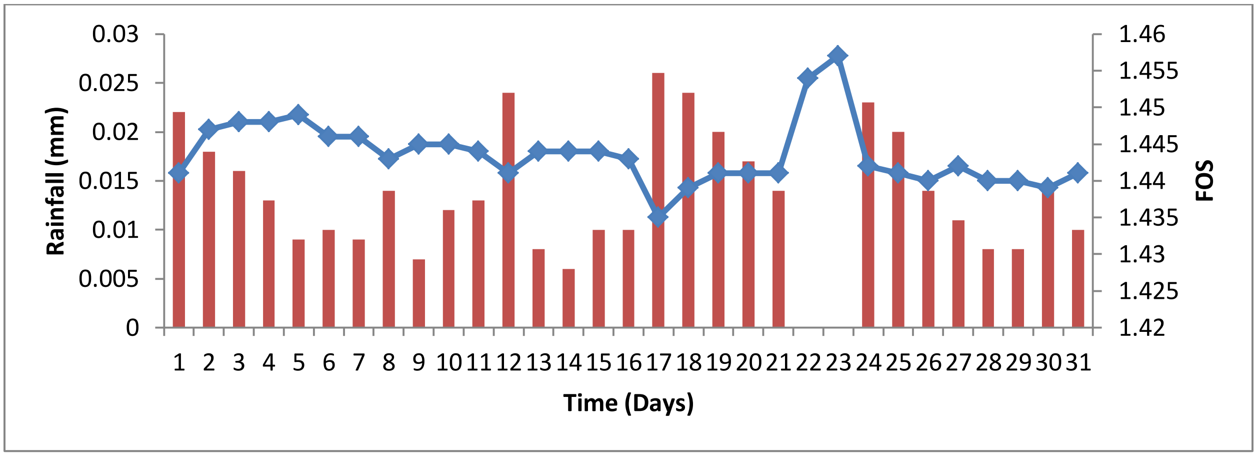

Fig. 5.7 10Km Sta. Landslide FoS Distribution in the critical month rainfall.

The factor of safety variation in the critical month of August generally shows an opposite pattern as the rainfall, which means on the days of high rainfall the FoS gets low as the dissipation of suction reduces the shear strength of the slope mass. On the other hand, on the days of null rainfall the stability coefficients increase as the development of suction increase the shear strength of the potential landslide.

A rainfall of 22mm was recordedat the beginning of the month and the respective factor of safety was 1.441, while as the days passes the rainfall amount decreases thereby the FoS increase.

The relationship of rainfall in the critical month and stability coefficients can be clearly observed on the days of high and low rainfall. As it is illustrated in fig. 6.7, on the days of high rainfall such as 12^{th}, 17^{th}, and 24^{th} of August the respective factor of safety were found to be 1.44, 1.435, and 1.442 respectively.

While, on the days of zero rainfall 22nd and 23rd of August, the stability coefficient gets 1.454 and 1.457 respectively.

The reason behind such variation in FoS is attributed to the development and dissipation of negative pore-pressure during null rainfall and rainy days respectively.

5.5.3. Stability and rainfall duration

In the present study, the seepage stability analysis at 10km sta. landslide on Gohatsion-Dejen road at the rainfall intensity of 84mm/day under the action 1-, 2-, and 3-days rainfall parameters were studied.

As previously discussed, the seepage profile for each rainfall duration simulations were imported from SEEP/W into SLOPE/W to compute the FoS. Including the analysis at initial condition (dry period) with the application of 84mm/day rainfall intensity for 1-, 2-, and 3-days duration, the variation of stability coefficient are shown in the fig. 6.8.

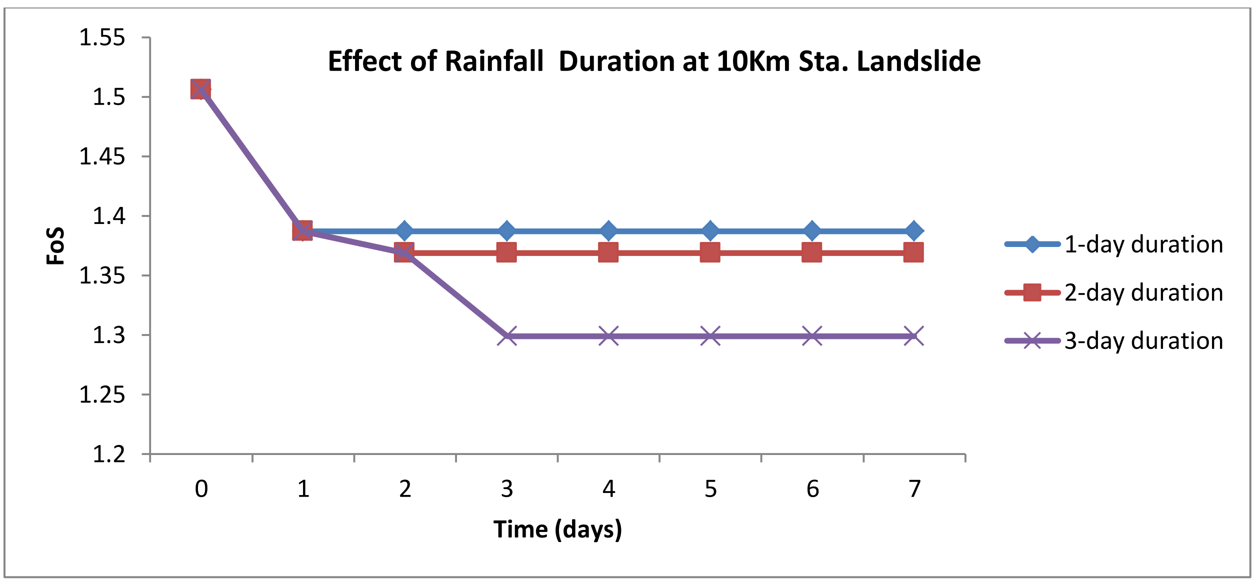

Fig. 5.8 stability results for different rainfall durations.

From the result of stability calculation in fig. 6.8, we can understand that with the extension of rainfall duration, the stability analysis of 10km sta. landslide aggravates and the FoS decrease quickly, demonstrating that, the 10km sta. landslide is significantly affected by rainfall durations.

When the rainfall duration is one day, the FoS decreased from its initial condition of 1.506 to 1.387. In similar fashion, the stability coefficient further drops to 1.36 at the end of 2-days rainfall duration. A FoS of 1.29 is computed after 3-days of 84mm/day rainfall at 10km sta. landslide.

The result of the analysis reveals that, landslide stability worsens and values of FoS decreases rapidly as the rainfall duration increases.

5.5.4. Stability and Rainfall Intensity

The effect of rainfall intensity on the stability of the selected landslide location on Gohatsion-Dejen road was demonstrated by imposing a 10%, 50% and 100% increment value on the maximum annual daily rainfall recorded at Filiklik gauging station as surface unit flux type boundary condition for one day duration on the landslide model in SLOPE/W.

The stability analysis result under the three type increment value rainfall intensities are shown in fig 6.9.

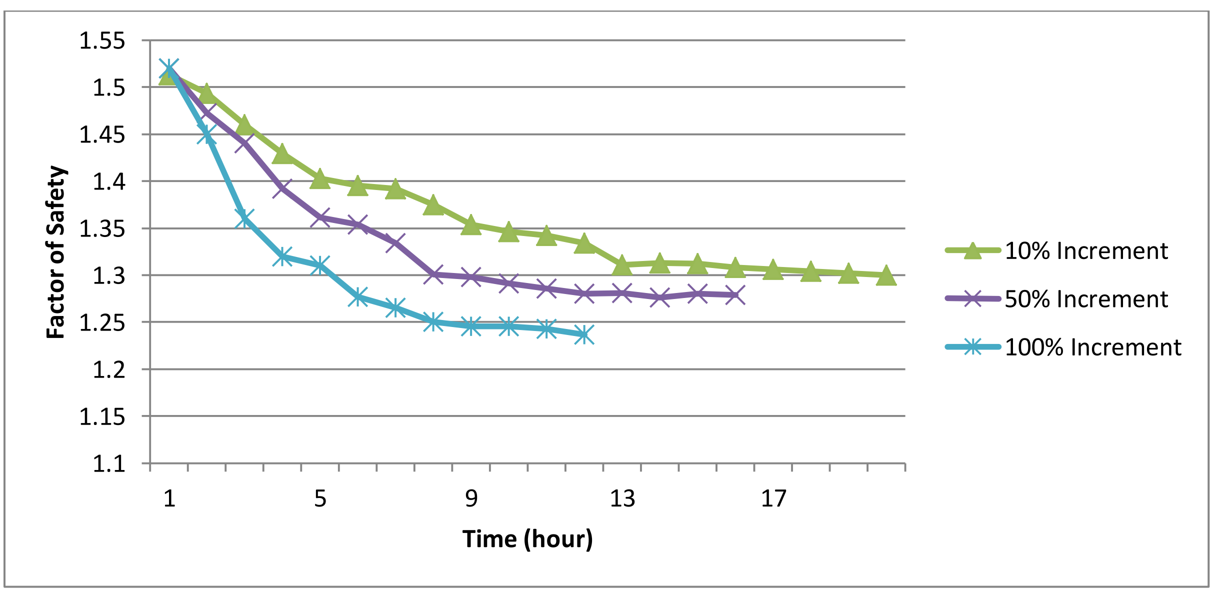

Fig. 5.9 Variation of factor of safety in different rainfall intensities

Generally, As it is clearly shown in the above figure, the factor of safety decrease as the rainfall intensity increments increases. And specifically, a 4.09% to 5.38% decrease in FoS was observed when the rainfall intensity increase from 92mm/day to 126mm/day. However, as the rainfall intensity increased by 100% (168mm/day), apparent decline in FoS were displayed by 5.56% reduction from 1.44 to 1.36.

From the stability analysis result for different rainfall intensities, it can be said that, the slope stability of 10km sta. landslide greatly depends on the degree of rainfall intensity.

6. Conclusion and Recommendation

6.1. Conclusion

Landslide slope failure due to rainfall is a common event along Gohatsion-Dejen road, in the Abay gorge.

The landslide causes considerable damage both on human life and properties. Specifically the nearly 41.5km long trunk road which crosses Abay gorge from the town of Gohatsion to Dejen, suffers a lot from frequent landslide slope failure. The failure was high during the rainy seasons indicating that, the possible triggering factor could be rainfall.

Despite the fact that, the government of Ethiopia with the aid from JICA undertook several regular inspections and counter measures along the road, the problem still persists and makes the transport work difficult and risky during the rainy season from the beginning of June to late September.

As a result a detail and factor specific site investigation and stability analysis, which takes into account all the triggering mechanisms along with frequent site inspection is mandatory for sustainable alleviation of landslide problem in the gorge.

The purpose of the paper is to investigate the effect of rainfall in causing landslide slope failure on Gohatsion-Dejen road in Abay Gorge. Besides, the paper also focused on conduction stability analysis of of potential landslide location due to rainfall, using coupled hydro-geological computer application called Geo-Studio 2007 software.

To achieve those objectives, review of theories and governing equations to analyze a rainfall induced stability along with evaluation of literatures and geophysical investigation reports of GSE have been discussed.

To investigate the influence of rainfall on landslide stability a case study has been conducted along Gohatsion-Dejen road at 10Km station. The site was selected based on its high value of risk for road and hazard score. Moreover, availability of geological and geotechnical data were also the other selection criteria to conduct the analysis.

The geomorphological along with the hydrological and topographical characteristics of the potential landslide location at 10Km sta. have been discussed.

A study period has been selected based on the number of days with rainfall per month in a year from the 19 years available rainfall data. Moreover, the effects of variation of rainfall duration and intensity on the 10km sta. landslide were analyzed and discussions on the results have been done.

A 2D finite element model has been developed specifically for the case study slope seepage analysis (both steady and transient) using SEEP/W, and the results of pore-water pressure distribution directly imported into SLOPE/W to compute the respective FoS of 10km sta. Landslide.

The following conclusion can be made from the analysis result:

[1] From coupled hydro-geological landslide stability analysis result at station 10km., it has been seen that, at initial condition (dry period) the developed pore-pressure was as high as -96.4kPa at the ground surface. However, as the dry period followed by intense rainfall such as the critical month (August), rainfall infiltration leads to the development of positive pore-water pressure or dissipation of suction to -16kPa and to finally above zero as rainfall advances.

This suction loss thereby reduces the shear strength of the slope mass which indicates that loss of negative pore-pressure due to rainfall is capable of causing landslide slope failure.

[2] The SLOPE/W result of the stability analysis at 10km Sta. potential landslide location reveals that, initially at dry period, the slope has a FoS of 1.506 which is acceptable in most geotechnical engineering practices.

However, during the critical month of rainfall the factor of safety shows a variation as shown in fig.6.7. The FoS is dropped as low as to 1.4 on days of high rainfall such as on 17^{th} August.

[3] As the landslide stability analysis for different rainfall duration and intensity clearly demonstrates in fig.6.8 & 6.9 respectively, the shear strength of unsaturated soils greatly related with the available negative pore-pressure.

When the duration of rainfall increase the advancement of saturated zone enlarges and the FoS decrease from 1.506 to 1.299 at the end of 3-day. Due to long duration and intense rainfall, the shear strength mobilized by suction between soil grains becomes weaker as positive pore-pressure develops.

Hence, it can be concluded that, suction plays a great role in keeping the 10Km sta. landslide stable.

[4] The major application of the stability analysis of landslides induced by rainfall lays on the development of landslide prediction and warning system. As this paper carried out the stability analysis of the 10km sta. landslide for the critical month of August, using the daily rainfall distribution as shown in fig. 6.7, it is possible to predict when the landslide at 10kn sta. becomes fully destabilized due to rainfall. A further precise result on prediction of landslide can be obtained by adopting hourly rainfall distribution data within a day if available. From the prediction of landslide failure a warning system can be prepared, to enable the respective authorities to reduce the damages on human life and properties due the landslide through early evacuation on and down the landslide area.

In addition, analysis of factor specific stability analysis like the present study will enable the government and the respective body to implement effective preventive measures. For instance, reducing rainfall infiltration by planting grasses on the ground surface and/or making the upper soils impermeable greatly minimize loss of suction thereby increase stability of the landslide.

6.2. Recommendation

Based on the landslide stability analysis of the 10km sta. on Gohatsion-Dejen road in Abay gorge using the coupled hydro-geological analysis model and obtained results the following recommendations are proposed for future research:

[1] In this study due to data limit constraints the stability analysis has been done by using the LEM. However, the analysis can also be done using FEM. Since FEM allows slope movement during analysis, it better captures the mechanism of slope failure. As a result for continues slope monitoring system and landside prediction FEM provides better result.

[2] In this study only static load due to self-weight of the slope mas and rainfall action are considered. However, including traffic load on the road and dynamic loads due to earthquake in the analysis could yield better simulation of the site condition

[3] In the present study the infiltration is simplified by assuming the recorded rainfall, however in reality the infiltration rate is a time dependent variable controlled by surface-sub-surface head difference and the hydraulic conductivity of the upper layer soil. Therefore, a coupled surface-sub-surface runoff and infiltration analysis provide a more reliable result.

[4] Due to collapse of boreholes and malfunction of measuring devices and equipment, it was difficult to obtain monitoring data specifically GWT level reading on the case study area and for the critical month of august. As a result, verification and validation of the results of the stability analysis was impossible. However, if monitoring data obtained, a more reliable result can be obtained from such coupled hydro-geological stability analysis.

[5] Regarding to the mitigation measures, all efforts should be made to reduce the rainfall amount infiltrated into the ground by making the upper layer

impermeable through planting grass such as vetiver grass. In addition, installing sub-surface drains in the slope mass will reduce positive pore-water pressure thereby the slope keep stable. Collecting and diverting surface water safely into downstream side also useful in reduction infiltration water to the ground.

[6] To take uncertainties in to consideration, it is recommended to undertake a reliability analysis by combining mathematics and engineering knowledge.

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Appendix I –Borehole log data

Appendix II –Landslide Distribution Map

Appendix III –Landslide Hazard Score Map

Appendix IV –Landslide Risk for Road Map